IMPROVEMENTS IN TROPICAL CYCLONE MOTION PREDICTION BY INCORPORATING DMSP WIND DIRECTION ESTIMATES

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THESIS

IMPROVEMENTS IN TROPICAL CYCLONE
MOTION PREDICTION BY INCORPORATING
DMSP WIND DIRECTION ESTIMATES

by

Thomas Paul Walters

June 1978

Thesis Advisor: R. L. Elsberry

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Improvements in Tropical Cyclone Motion Prediction by Incorporating DMSP Wind Direction Estimates		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; June 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Thomas Paul Walters		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, CA 93940		12. REPORT DATE June 1978
		13. NUMBER OF PAGES 72
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, CA 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Improvements in Tropical Cyclone Motion Prediction by Incorporating DMSP Wind Direction Estimates

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
June 1978

ABSTRACT

The wind fields used to initialize a coarse grid tropical cyclone motion prediction model were re-analyzed to include wind direction estimates based on Defense Meteorological Satellite Program (DMSP) photographs. An average of 20 upper-level direction estimates based on cirrus streaks and 17 low-level directions were available for the 32 cases considered. A modified version of the Barnes (1973) objective analysis scheme was used to re-analyze the initial fields provided the model. A control experiment with an analytic representation of a typhoon embedded in a basic current was used to test the effects of data distribution in the objective analysis scheme. Although a direct re-analysis of wind direction was useful in the region of the typhoon, a scheme for analyzing the u and v components was adopted. The speed at the location of the wind direction estimate was interpolated from the first guess wind field provided by Fleet Numerical Weather Central. Track forecast errors for the tropical cyclone model initialized with the new analyses including the satellite data were compared with model forecast errors based on the original wind analyses. The inclusion of the DMSP direction estimates failed to improve the error statistics for the 32 cases from the 1975 season. Improved forecast accuracy occurred only when the incorporation of the DMSP wind direction estimates produced significant improvements in the wind fields in the immediate vicinity of the storm or in areas into which the storm eventually tracked. The incorporation of direction estimates located on the periphery of typhoons failed to re-direct the initial storm motion.

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor R. L. Elsberry for his patient guidance during the course of this research. Special thanks are extended to Ed Barker and Rich Hodur of Naval Environmental Prediction Research Facility (NEPRF) whose interest and continual assistance made the study possible. The author also wishes to thank Professors G. J. Haltiner and R. T. Williams for reviewing the manuscript and making several useful suggestions. Appreciation is extended to Capt. (USAF) E. L. McCormick whose computer expertise was invaluable in solving several technical problems. The author is especially grateful to his wife, Cecilia, for her patience and unyielding support throughout the period of research.

I. INTRODUCTION

The typhoon is one of nature's most destructive phenomena and, as such, has long been a focal point of weather prediction in the tropics. Military and economic considerations, as well as possible loss of life, necessitate an accurate, advanced warning of both storm strength and movement. Recent numerical experiments have realistically simulated many of the characteristics of mature tropical cyclones, including development and intensity (Anthes, 1974). Unfortunately these highly-sophisticated numerical models are either not easily adapted to operational use or have not consistently yielded satisfactory predictions of storm tracks. One of the primary reasons for the inability of tropical cyclone models to accurately forecast storm movement is the lack of accurate, real-time data available for model initialization (George, et al., 1976). Observations over ocean areas have been limited by a sparse network of rawinsonde stations and minimal aircraft reconnaissance. At any one time, there are too few observations in the proximity of a tropical storm to define adequately the storm's environment. Even the most sophisticated models yield poor results when initialized with fields derived from scarce or incorrect observations. It is hypothesized (Hovermale, et al., 1977) that detailed storm structure is not required to forecast a tropical cyclone's movement as long as the large-scale flow is defined. Data scarcity, however, can make even the large-scale flow questionable. With the advent of meteorological satellite programs, wind observations derived from cloud motion vectors or wind directions estimated from individual photographs can be available

on a routine basis. Elsberry (1977) showed that wind direction estimates based on DMSP imagery should be useful in supplementing routine observations and in better defining the fields used to initialize tropical cyclone models. During 1975 wind directions were estimated for upper and lower levels by personnel at Anderson AFB, Guam from high-resolution DMSP imagery. These estimates, considered experimental during 1975, were not incorporated into the Navy's operationally analyzed wind fields until 1976.

The official warnings for tropical storms in the western Pacific are issued by the Joint Typhoon Warning Center, Guam, Mariana Islands (JTWC). These forecasts are a subjective modification of statistical and numerical track predictions and persistence. The numerical predictions considered are the results of a primitive-equation, three-layer Tropical Cyclone Model (TCM) run by Fleet Numerical Weather Central, Monterey, California (FNWC). An evaluation of the results of the TCM for the 1975 tropical cyclone season (Elsberry, 1977) concluded that one principal source of error was related to data deficiencies in the global band upper air analyses (GBUA) used to initialize the model.

Results of the TCM for 1975 tropical storms in the western Pacific were rather poor with mean 24-, 48- and 72-hour forecast errors of 155, 253, and 437 nautical miles respectively. The results for the 1976 season showed an overall improvement, especially for the 72-hour forecast which had a mean error of 375 nautical miles (Hinsman, 1977). The improvement for the 1976 season has been attributed to an improved method of bogusing typhoon circulation into middle and upper GBUA fields. It is probable that the improvement was also due to the addition of DMSP wind direction estimates to the GBUA data base.

The problem confronted by this thesis was the inadequate and often erroneous data base used to initialize the TCM during the 1975 season. The hypothesis is that an objective analysis scheme which updates the GBUA fields by incorporating the DMSP wind direction estimates into the data base should create more representative initial fields. In turn, these fields should result in improved tropical cyclone motion forecasts. An evaluation of the wind directions from the 1975 GBUA fields and the DMSP estimates is presented to illustrate the reliability of the DMSP estimates and the discrepancies which exist between the two data sources.

A modified mesoscale objective analysis scheme after Barnes (1973) was used to re-analyze the input fields provided the TCM during the 1975 typhoon season. Two basic approaches to the objective analysis scheme were considered. The first approach combined the wind direction estimates with velocities interpolated from the GBUA fields to yield wind vector estimates. These new "observations" were then decomposed into u and v components which were objectively analyzed into the appropriate GBUA fields. In the second approach the wind direction fields were re-analyzed based on the differences between the DMSP wind directions and the GBUA directions at the same locations. Both methods were evaluated to see how well each could represent the circulation field associated with a tropical cyclone.

It is important to note that both of these approaches involve an adjustment to the analyzed GBUA wind fields using only DMSP wind direction estimates at a single time. This is in contrast to the 1976 season where the DMSP direction estimates were incorporated with other wind observations in the regular GBUA routine. Because the GBUA uses the previous analysis as a first guess, the DMSP wind estimates entered at

a particular time could have a continuing beneficial effect in normally data-void regions. This cumulative effect could not be attained with the individual 1975 typhoon cases treated here.

Using the first approach of updating the GBUA fields, the effects of the DMSP wind direction estimates on TCM performance were investigated for thirty-two 1975 cases. As a comparison, control cases were run in which the TCM was initialized using the original GBUA fields. The forecasts of both the control cases and the runs using the updated initial fields were compared with the best tracks as published in the Annual Typhoon Report (1975). The seasonal statistics based on effects of the new data source and the results of two specific cases are presented.

II. THE TROPICAL CYCLONE MODEL

A. THE MODEL

The Tropical Cyclone Model is a three-layer primitive-equation model in pressure coordinates. The model was initially developed by Elsberry and Harrison (1971) and improved by Harrison (1973). It is a channeled model with free slip conditions on the north and south walls, and cyclic conditions on the east and west boundaries. The horizontal grid is a Mercator projection with 2° latitude grid increments. A complete discussion of the model and its characteristics may be found in Ley (1975).

B. INITIALIZATION

As discussed by Anthes (1974), geostrophic adjustment theory indicates that the mass field will adjust to the initial wind field for scales of motion appropriate to tropical cyclones. Consequently, primary consideration must be given to the wind fields during the diagnostic phase of the TCM. This fact leads to the initialization in a manner quite different than in extratropical models. In a mid-latitude model, the wind is normally derived from a solution of the balance equation with an objectively analyzed geopotential field (Haltiner, 1971). During the diagnostic phase of the TCM, non-divergent winds at 850, 550, and 250 mb are calculated from the initial wind fields. The geopotential fields are determined from the subsequent solution of a balance equation.

The wind data used for the initialization of the 1975 cases were from the GBUA supplied by FNWC. These operationally analyzed fields are modified by inserting a symmetric typhoon circulation at the gradient

level only (Numerical Environmental Products Manual, 1975). The location and intensity of this typhoon are based on the JTWC warnings. Although the numerical variational method used in creating the GBUA causes a weak typhoon circulation at higher GBUA levels, this circulation diminishes with height and the resulting fields are rarely representative of the structure and environment of the actual storms.

III. DMSP WIND DIRECTION ESTIMATES

A. SOURCE

The DMSP wind direction estimates were provided at lower and upper levels by JTWC. As shown in Table I, the number of estimates that fell within the domain of the TCM averaged 17 per day at the gradient level and 20 per day at the upper level. These estimates were derived from the orientation of clouds as depicted on DMSP visual imagery. The low-level direction estimates are based on the orientation of cumulus cloud clusters. Accurate estimates of the flow at upper levels are obtained from cirrus streamers. Upper-level wind direction estimates in regions of strong winds have been shown to have a probable uncertainty no greater than $\pm$ 10° (Johnson, 1966); however, the estimates become more unreliable as the wind speed decreases. When the wind speed is less than 20 knots, the wind direction is variable causing the correlation between cirrus orientation and wind direction to be questionable (Anderson, et al., 1969). The outflow associated with tropical cyclones provides a large number of potential direction estimates. Consequently, it is assumed that all upper-level direction estimates provided by JTWC are based upon well-defined cirrus streamers associated with winds in excess of 20 knots.

By comparing radar winds and satellite cloud tracer motions, Hubert and Whitney (1971) found that cirrus and cumulus clouds were most nearly representative of the wind motions at 200 and 850 mb respectively. Based on these results, the low-level DMSP wind direction estimates were considered to be at the 850-mb level of the TCM. For convenience, the upper-level direction estimates were assumed to approximate the flow at the 250-mb level.

TABLE I

Storm	Day	850-mb	250-mb	Storm	Day	850-mb	250-mb
NINA	8/2	0	22	CORA	10/2	12	37
	8/3	8	17		10/3	0	34
ORA	8/11	0	18		10/4	0	21
PHYLLIS	8/14	22	27	ELSIE	10/10	20	30
	8/15	13	13		10/11	1	33
	8/16	0	19		10/12	13	22
RITA	8/21	23	11		10/13	10	9
	8/22	13	7	FLOSSIE	10/21	8	9
TESS	9/3	34	32		10/22	16	18
	9/5	21	16	IDA	11/8	20	25
WINNIE	9/10	16	19	JUNE	11/17	22	14
ALICE	9/17	11	12		11/18	39	33
	9/18	19	18		11/19	24	18
	9/19	13	7		11/20	25	16
BETTY	9/20	10	15		11/21	5	12
	9/21	22	27				
	9/22	16	22				

Level	Days	Number	Average
850-mb	27	456	17
250-mb	32	633	20

Number of DMSP-derived wind direction estimates within the domain of the tropical cyclone model for 1975 typhoons.

B. EVALUATION

The 250-mb GBUA and DMSP wind directions were compared for both the 1975 and 1976 seasons to evaluate the potential effect of including the DMSP directions in the data base. This comparison follows the technique of Elsberry (1977). Wind directions to the nearest 10 degrees were bilinearly interpolated from the appropriate GBUA fields at the same locations for which DMSP wind estimates were available. For a standard of comparison, the hand-analyzed streamlines prepared by JTWC were considered "ground truth". During 1975, the DMSP direction estimates were available to the JTWC analysts, but were regarded as experimental. During 1976, these estimates were available to both the JTWC analysts and the objective analysis technique which produces the GBUA.

In spite of the fact that the DMSP direction estimates were available to the JTWC analysts, the comparison of the DMSP estimates and the JTWC analyses is a useful indication of the reliability of the estimates. If sufficient data are available in the vicinity of DMSP estimates, and the subsequent analysis agrees with the DMSP directions, then the comparison indicates that the DMSP estimates are reliable. If, however, the direction estimates fall in regions of sparse data, and the JTWC analysis still agrees with the estimates, the comparison may be an indication of the degree to which the analyst relied upon the estimate. With only minimal data available to the analyst, an indication that he relied upon the direction estimate can be considered a measure of how well the estimate fits the overall wind pattern. The comparison of the GBUA and the JTWC wind directions gives a measure of the degree to which the initial fields provided the TCM represent the wind fields as analyzed by JTWC. An evaluation of these comparisons for the 1975 and 1976

typhoon seasons should yield an indication of the effect of adding the DMSP direction estimates to the GBUA data base. This is only an indirect indication of the actual improvement of the GBUA fields because all the direction estimates may not be available in the GBUA data base, and the objective analysis scheme may not correctly reject all poor estimates.

A total of 671 and 730 upper-level wind direction estimates were available for 1975 and 1976 respectively. The differences between the directions of the JTWC analysis and the DMSP estimates are indicated in the top portions of the histogram in Figs. 1 and 2. The percentage of DMSP estimates which were identical to ground truth rose from 49% to 63% from 1975 to 1976. This indicates an increased confidence in the DMSP estimates on the part of the JTWC analysts. This confidence is emphasized by the fact that approximately 70% of the DMSP direction estimates for both years lie within $\pm$ 10° of the hand-analyzed fields. For both seasons the mean direction differences as indicated in Table II are insignificant and are nearly equal to zero. The root-mean-square differences of 37° and 40° for 1975 and 1976 respectively are rather large but can be explained by observations on the extreme wings of the distribution.

The differences between the GBUA and the JTWC wind directions are indicated in the bottom portions of the histograms in Figs. 1 and 2. The broad distributions shown for both seasons are indicative of the large differences in directions between the JTWC hand-analyses and the fields used in the diagnostic phase of the TCM. Only 21% of the GBUA winds are within $\pm$ 10° of the JTWC streamlines in 1975. This figure increases to 31% for the 1976 season. There is an average bias in the

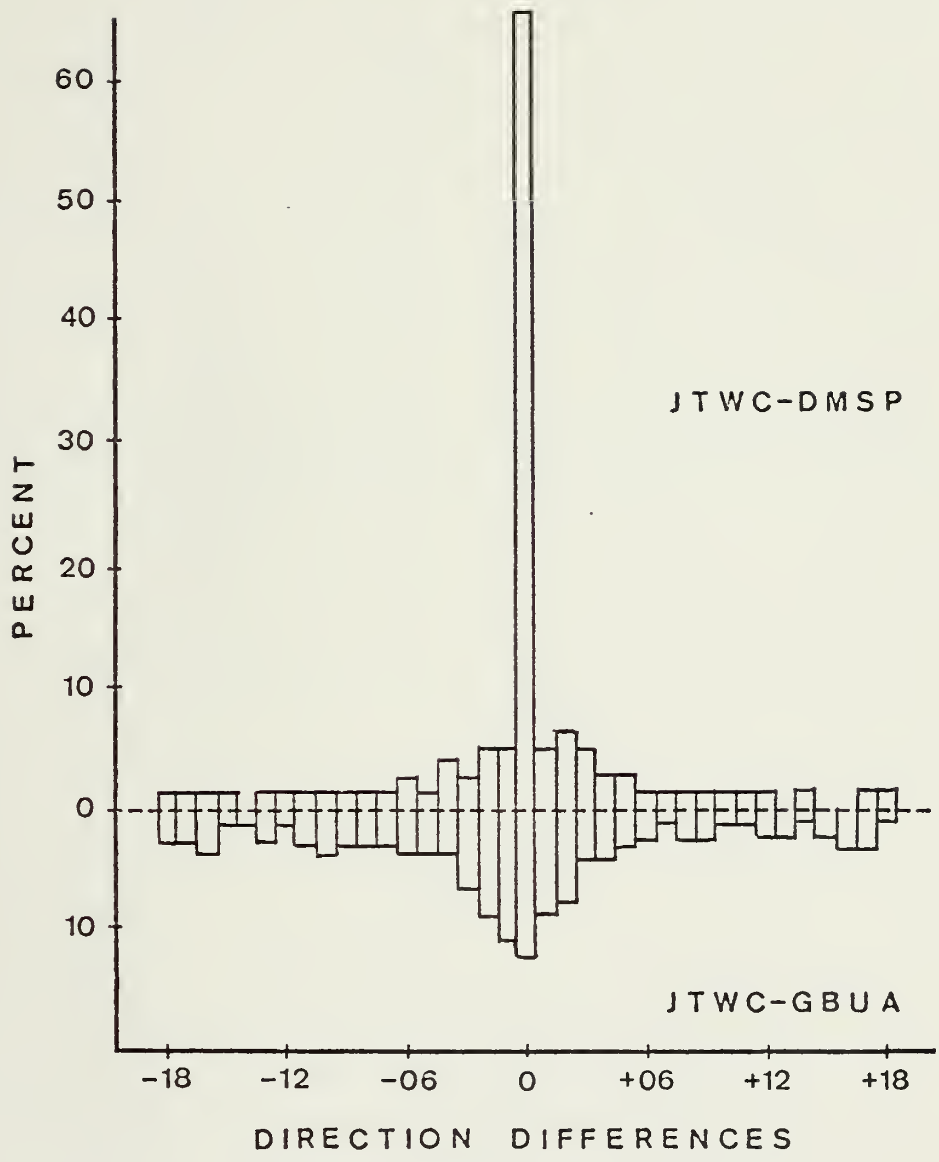

Fig. 1. Histogram of 250-mb direction differences (tens of degrees) for JTWC-DMSP (top) and JTWC-GBUA (bottom) for 1975.

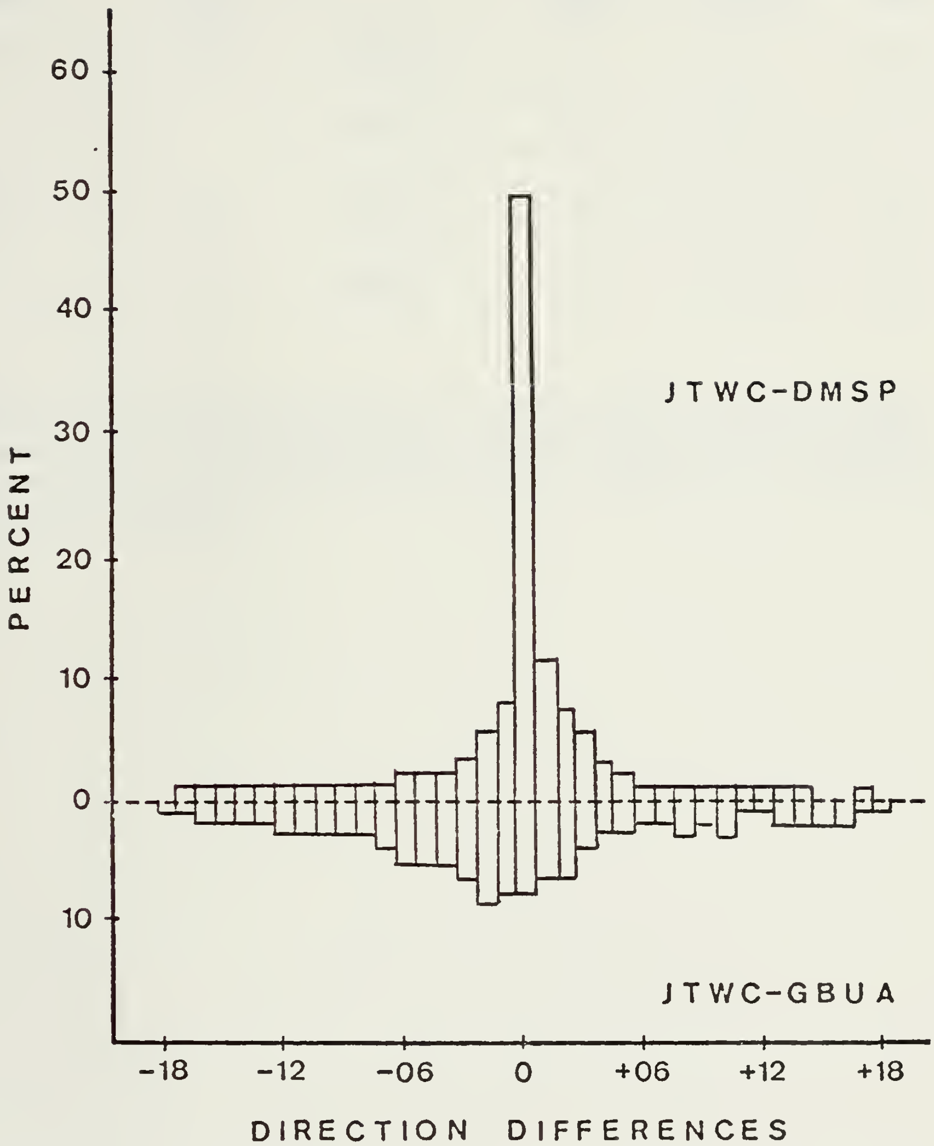

Fig. 2. Same as Fig. 1 except for 1976.

TABLE II

Typhoon Season	Sample Size		Direction Differences Mean	Median	RMS
1975	671	DMSP	-1	0	37
		GBUA	-12	-10	75
1976	730	DMSP	-2	0	40
		GBUA	-2	0	76

Summary of 250 mb wind direction differences (degrees) from hand-analyzed JTWC streamlines for the DMSP-derived direction estimates and the global band upper air (GBUA) directions at the same locations.

GBUA directions of 12° clockwise of the ground truth in 1975. The median value of this bias is 10° clockwise. During 1976 the average bias is reduced to 2° clockwise and is nearly equal to the median of zero. This improvement can be explained by the addition of the upper-level bogused outflow and the DMSP direction estimates to the GBUA fields. In spite of this improvement, the root-mean-square difference of 76° indicates that the upper-level wind directions available as input for the TCM are often from the wrong quadrant. Consequently, even the 1976 GBUA fields fail to accurately represent the atmospheric flow associated with the tropical cyclones of that year.

To emphasize the discrepancies between the 1975 GBUA winds and the DMSP direction estimates, the initial 250-mb wind field used by the TCM for Typhoon June on 18 November 1975 is shown in Fig. 3. Superimposed on this figure are the DMSP wind direction estimates. The DMSP direction estimates appear to be internally consistent. Only the estimate at 20N 155E does not conform to the flow pattern defined by the other observations. The DMSP and GBUA winds, however, appear to be totally inconsistent, and certainly do not define the same flow pattern. Since most of the DMSP direction estimates are not located close to the typhoon warning position, a re-analysis of the GBUA winds with heavy reliability weights given the direction estimates should provide a more representative large-scale wind structure.

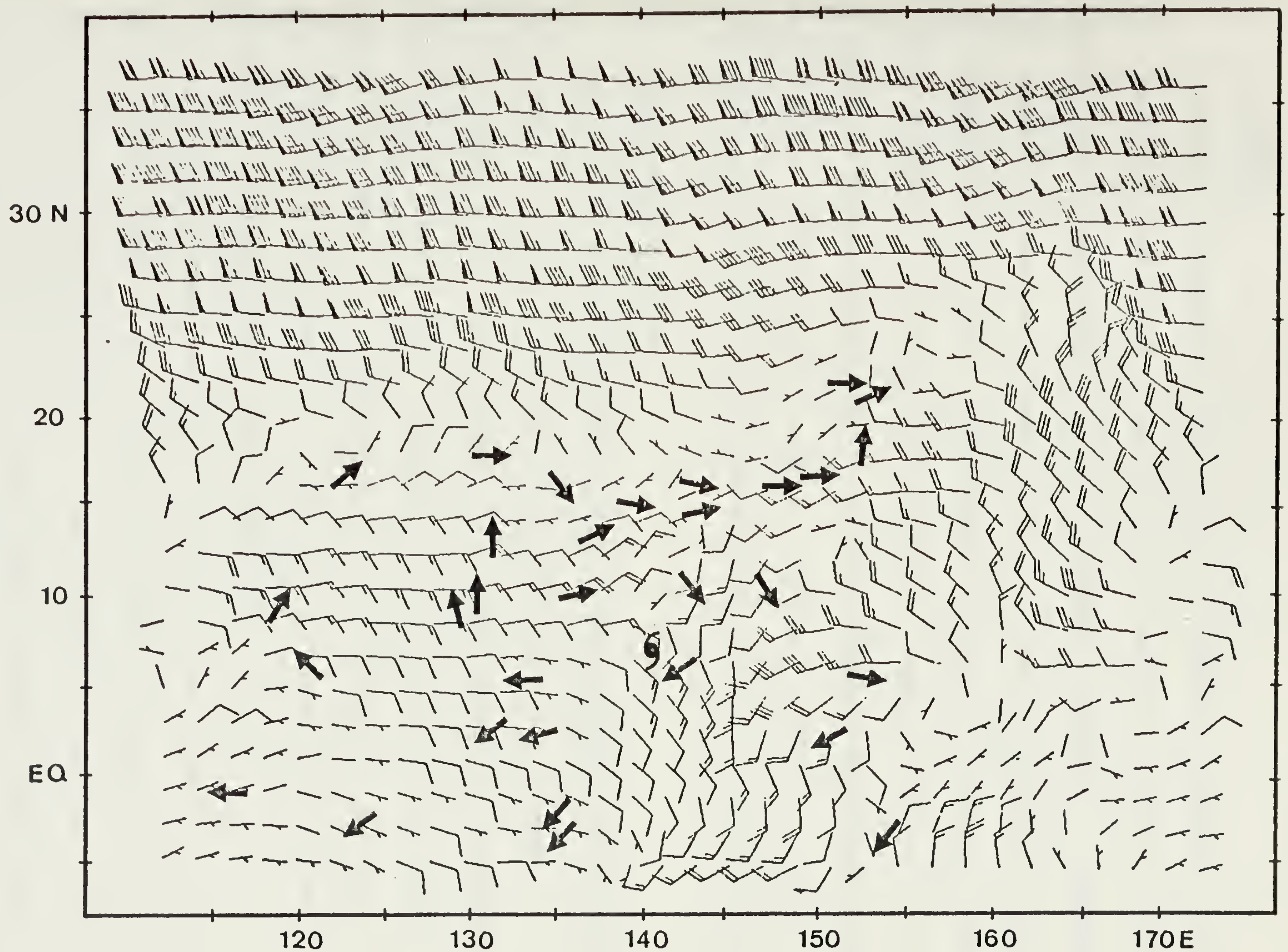

Fig. 3. Original 250-mb wind field and DMSP wind direction estimates (→) for Typhoon June, 00GMT, 18 November 1975.

IV. THE OBJECTIVE ANALYSIS SCHEME

A. THE SCHEME

The basic tool used to incorporate the DMSP wind direction estimates into the 1975 GBUA fields is an objective analysis scheme developed at the National Severe Storms Laboratory, Norman, Oklahoma. A summary of the scheme is presented in the Appendix. A more complete discussion may be found in Barnes (1973). The scheme is similar to Cressman's method (1959) in that it uses weighted averages of observed data to make corrections to an initial guess field. Unlike Cressman's method of successive corrections, Barnes' method requires only one iteration (2 passes) to obtain the desired fit of the interpolated field to the new observations.

B. SCHEME MODIFICATIONS

The objective analysis scheme used in this research was originally developed for use with mesoscale data distributions. Consequently, minor modifications and the determination of several empirical parameters had to be accomplished prior to inserting the scheme into the diagnostic phase of the TCM. For simplification all distances and distance related parameters were calculated in terms of grid intervals as opposed to kilometers as presented by Barnes (1973).

The analysis scheme corrects each first guess value by a weighted amount proportional to the difference between the observation and the first guess field interpolated to the observation location. The fraction of the correction made at each grid point decreases exponentially as the distance from the observation increases. In the mesoscale version of the analysis scheme, inserting one observation causes adjustments to all

first guess values. Since the adjustments at distant grid points are extremely small, the scheme is modified to allow corrections only in a smaller scan grid centered about each observation. The selection of the size of this scan grid is highly dependent upon observation density. If the size of this grid is too small, such that the grids centered on adjacent observations fail to overlap, the resulting weight-averaged field may not adequately represent the circulation features defined by the observations. The circulation resolution will improve as the number of observations in each scan increases. The limited number of DMSP wind direction estimates available for most 1975 typhoons required the selection of a relatively large scan grid. Several grid sizes were evaluated with a given observation distribution to see how well each represented the circulation associated with a tropical cyclone. This evaluation resulted in the decision to use a 21-by-21 grid for all objective analyses.

The exponential decrease of the corrections to the first guess field is determined by an arbitrary parameter, K. As pointed out in the Appendix, the value of K is dependent upon the wavelength of the circulation features to be represented and the data distribution. Several values of K were evaluated using the wind component corrections approach presented in the following section. For use with a 21-by-21 scan grid, a K value of 25 $(\text{grid intervals})^2$ was determined to yield the best representation of the flow associated with a tropical cyclone, when only a limited number of observations is available.

Barnes (1973) evaluated the use of an elliptic along-the-wind enhancement of the weighting function (see Appendix). This enhancement has the effect of producing the largest corrections to the first guess field up- and downwind of the observation locations. The ratio of the major to

minor axis of the elliptic correction field is a function of the ratio of the wind speed at the observation location to some "characteristic" wind speed. Barnes' mesoscale evaluation concluded that upper air analyses are insensitive to this enhancement except when the actual wind speeds exceed the "characteristic" speed by a factor of two or more. In spite of this result, it seemed reasonable that the enhancement would improve the representation of the structure of a tropical cyclone. If a large number of observations are evenly distributed around a tropical cyclone which has been bogused into a first guess field, their addition to that field will better define the storm's structure. If, however, the available observations are limited by either number or distribution, the results of an isotropic weighting scheme will improve the representation of the circulation in the vicinity of the observations, while distorting it on the opposite side of the storm. This distortion in a region of rapidly changing wind direction is a direct result of data distribution. An evaluation of the along-the-wind enhancement using a "characteristic" wind speed of 25 m s^{-1} showed that the elliptic correction field improves the representation of a typhoon's circulation in the vicinity of the observations, while minimizing negative effects across the storm. The use of the along-the-wind enhancement results in only minimal changes to the large-scale flow in regions away from tropical storms. As a result of this evaluation, the elliptic enhancement was used in all objective analyses of DMSP wind direction estimates into the GBUA fields.

Updating the initial 850- and 250-mb wind fields without changing the winds at the 550-mb level has the potential of creating large, unrealistic vertical wind shears. To avoid this problem, the 550-mb winds were adjusted by one-tenth the value of the corrections at the corresponding 850- and 250-mb grid points.

C. WIND COMPONENT CORRECTIONS

The first approach attempted in updating the original GBUA fields required that a wind speed be interpolated from the appropriate GBUA fields at the location of each DMSP wind direction estimate. The direction estimates, together with the interpolated speeds, became the new observations which were used to update the GBUA. These observations were separated into u and v components, and the objective analysis scheme was applied to each component separately. The resulting wind directions of the updated fields were combined with the corresponding speeds of the original GBUA fields to produce the initial fields for the TCM. In this manner, only wind directions were altered. This version of the objective analysis scheme is designated the original component scheme for future references. A control experiment was used to evaluate the ability of the original component scheme to reconstruct a sinusoidal basic flow with an embedded tropical cyclone. An analytical solution composed of a symmetric typhoon located in an easterly wave was defined on a grid of identical dimensions as that used by the TCM. The wind characteristics of the typhoon were defined by establishing a radius of maximum wind of 20 nautical miles and a maximum cyclonic tangential wind of 140 knots. Thirty-seven winds were interpolated from the analytical solution at the locations corresponding to the DMSP wind direction estimates available for Typhoon June. The locations of these winds are superimposed on the analytical solution shown in Fig. 4.

The interpolated winds (essentially with no error components) were objectively analyzed into a first guess field consisting of zero u and v wind components. The analytical solution would have been reconstructed had all the winds from the analytical solution been available for the

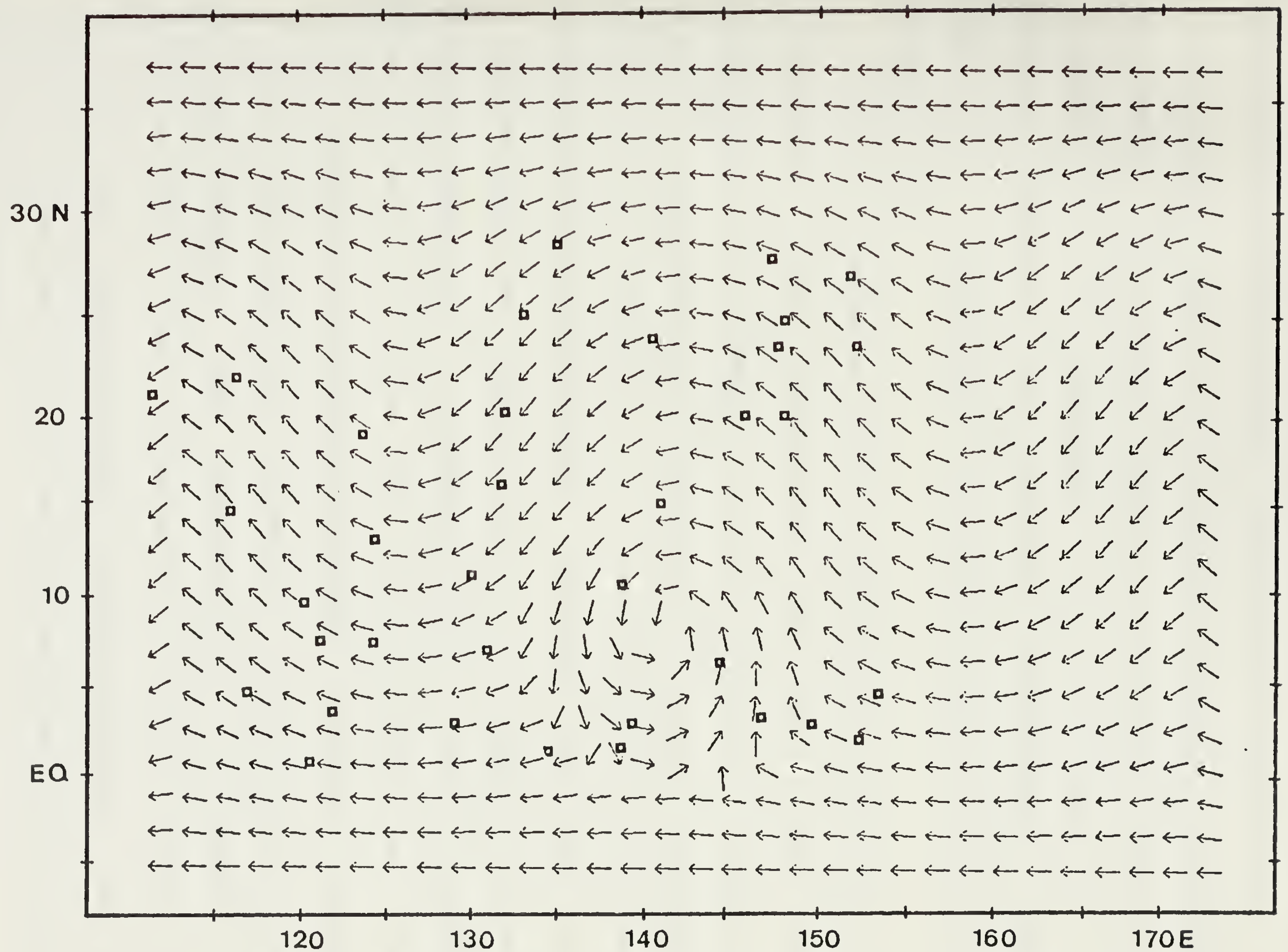

Fig. 4. Analytical solution for evaluation of original component correction scheme. Control experiment winds interpolated from indicated locations (□).

objective analysis. Using only a limited number of observations, as were available for the 1975 typhoon season, the results were as shown in Fig. 5. A comparison of the analytical solution with Fig. 5 shows that the results of the objective analysis satisfactorily represents the large-scale sinusoidal flow only in the region of the greatest observational data density. The easternmost ridge in the analytical solution is not represented due to data limitations. Not only are there too few observations near the ridge, the only observations available depict northwesterly flow. Consequently, the objective analysis eliminated the ridge entirely.

Although the objective analysis represents the cyclonic flow associated with the typhoon, the circulation depicted is too weak and has been shifted to the southwest of the actual position. To insure that the use of this approach would not destroy the typhoon circulation bogused into the GBUA fields, an exponential background weight was used with the objective analysis scheme. The initial weight given the first guess GBUA fields was a maximum value of 8 at the typhoon's center and decreased exponentially to a constant value of 2 five grid intervals from the center of the storm. This initial weighting scheme insures that the largest changes made by the objective analysis of new observations are to the large-scale flow pattern with only minimal changes to the vortex structure. Such a weighting scheme is not required by the operational GBUA routine. Operationally, the objective analysis would first have been completed including the DMSP observations. Then the bogus would have been added to a smoothed background field to represent the typhoon circulation.

A modified version of the original component correction scheme was evaluated and used in the TCM forecasts for a limited number of cases.

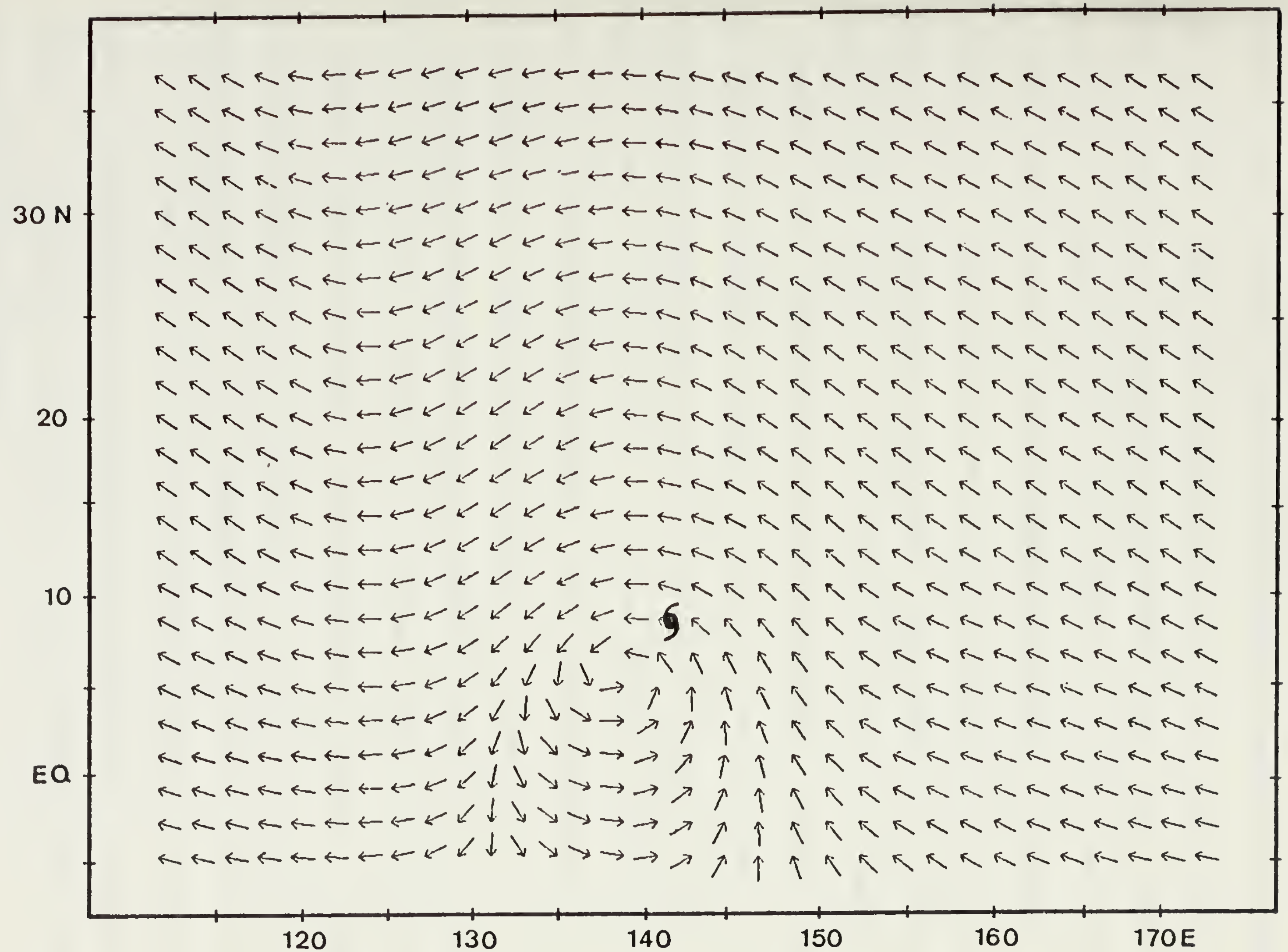

Fig. 5. Wind field produced by original component-scheme analysis of 37 winds taken from analytical solution in Fig. 4. Analytical solution typhoon location is indicated by typhoon symbol (🌀).

The modification was based on the assumption that upper-level wind directions were estimated from well-defined cirrus streamers associated with winds of 20 knots or greater. Wind speeds were interpolated from the first guess fields at each location for which direction estimates were available. Wind vector estimates for 250 mb were produced by combining the direction estimates with the corresponding first guess speed if that speed exceeded 20 knots. If, however, the first guess speed was less than 20 knots, a 20-knot minimum was assumed. The speeds for low-level wind vector estimates were interpolated from the first guess fields, but no minimum speed was imposed. This version of the objective analysis scheme results in larger upper-level directional changes in the regions of weak GBUA winds than does the original component scheme and increases the speeds of upper-level winds at low latitudes. The wind directions and speeds which resulted from the incorporation of the modified vector estimate components into the original GBUA fields were used as input for the TCM to evaluate the results of assuming a 20-knot minimum. The results of this evaluation are presented in Section V.

Using either component correction technique discussed, the incorporation of an observation located near a typhoon results in opposing effects on opposite sides of the storm. The analysis of a low-level southwest wind located in the southwest quadrant of a symmetrically bogused typhoon increases the positive u and v components of the winds in the first guess fields. This has the effect of increasing the confluence in the southwest quadrant of the storm, while decreasing the confluence in the northeast quadrant. To circumvent this problem, a second approach based only on wind directions was attempted.

D. WIND DIRECTION CORRECTIONS

This approach continued to use Barnes' objective analysis scheme; however, corrections were made directly to wind directions rather than to u and v components. In this approach, the wind directions of the GBUA fields represent the first guess values. The corrections made to these directions are based upon their differences from the DMSP wind direction estimates. This approach has the effect of backing all the winds in the 21-by-21 scan grid when a southwest DMSP wind estimate is analyzed at the location of a northwest first guess wind. The result of this method is to increase the low-level confluence on all sides of a typhoon when the direction estimate indicates more confluence than is present in the first guess field.

While this approach is useful in converting the winds of a symmetrically bogused typhoon into a more realistic structure, problems are encountered in the representation of the large-scale flow in areas of rapidly changing wind directions. This is indicated in the results of objectively analyzing the 250-mb DMSP wind direction estimates into the GBUA field for Typhoon June on 18 November 1975 (see Fig. 3). The results of the re-analyses using the original wind component correction technique and the direction correction technique are shown in Figs. 6 and 7, respectively. The varying results of the two approaches can be emphasized by focusing on the wind estimate from 240° incorporated into the original field at 19°N - 124°E (Fig. 3). The first guess at that location is a wind from 70°. Objectively analyzing the u and v components of the observation results in an increase in the positive u and v components in the first guess field; therefore, the winds in the vicinity of the observation become more southwesterly as indicated in Fig. 6. The objective analysis of the same observation based upon wind directions results in a tendency to veer

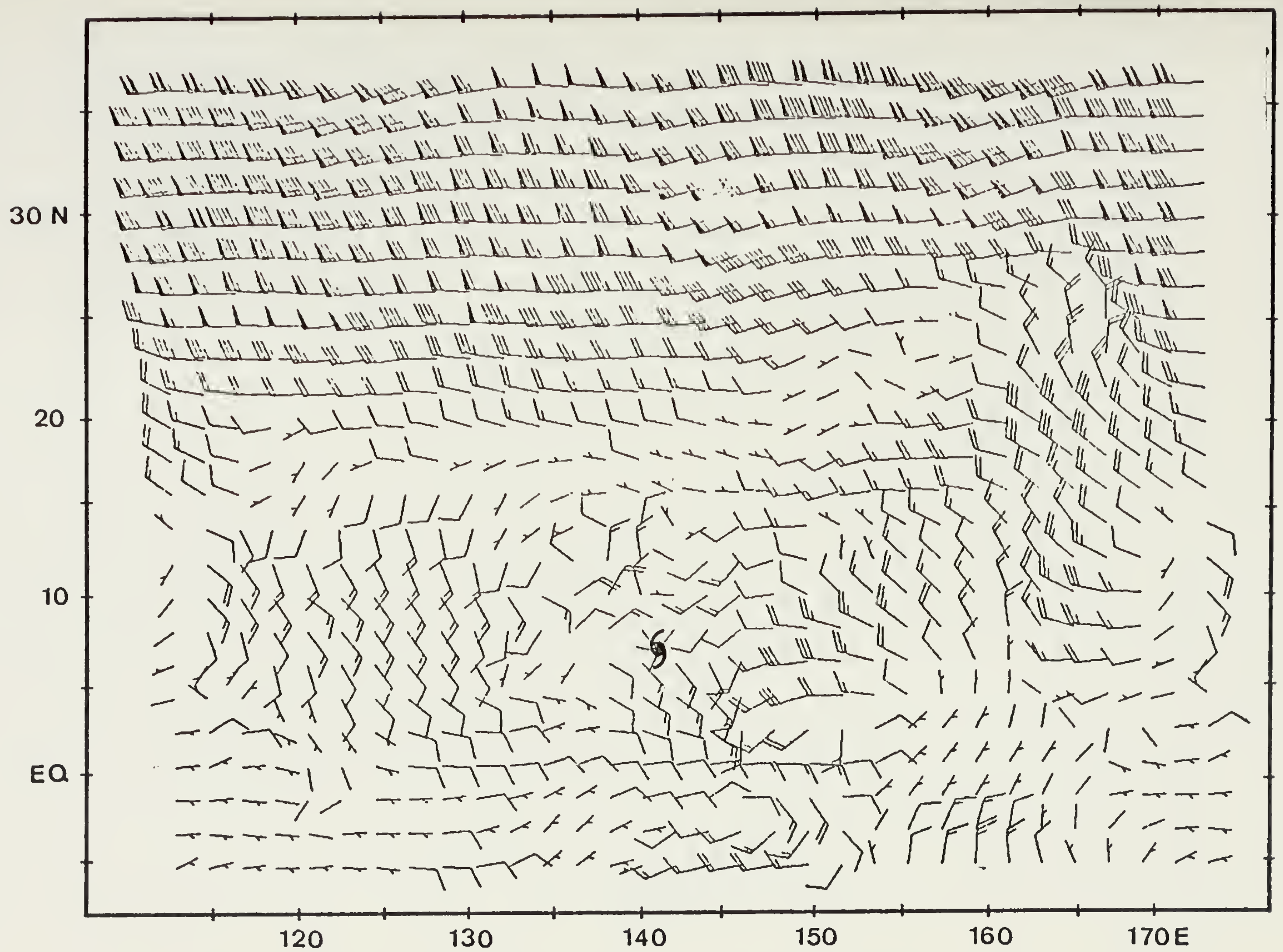

Fig. 6. Result of incorporating 31 DMSP direction estimates into 250-mb wind field shown in Fig. 3 using original component scheme.

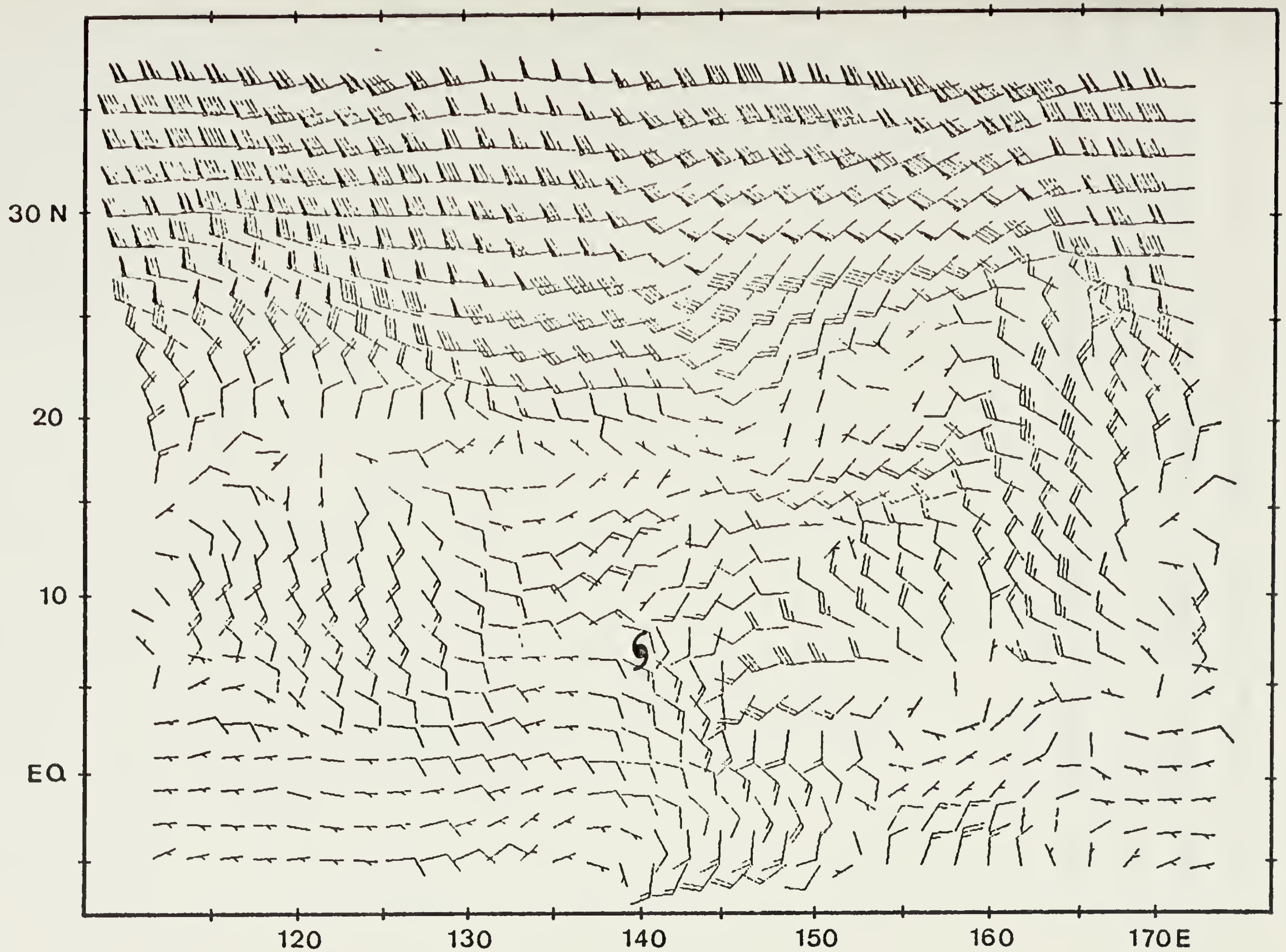

Fig. 7. Same as Fig. 6 except with re-analysis based on wind direction corrections.

all the first guess winds near the observation. This creates unsatisfactory results just north of the observation where the first guess winds change rapidly from northeast to west. Using this approach, the strong west winds of the first guess field are veered to the northwest. The failure of this method to represent the large-scale flow in regions of rapidly changing winds led to the use of the wind component objective analysis approach for all updates of the GBUA fields.

V. RESULTS

Forecasts based upon wind fields re-analyzed using the original component scheme were made for all 1975 typhoons for which DMSP wind direction estimates were available. Seasonal statistics and the results of two cases in which forecast tracks were significantly improved by the re-analyses are presented in this section.

A. TYPHOON JUNE

Super Typhoon June was the last typhoon of 1975, but was the most intense Pacific storm on record. June first developed in the Caroline Islands on 16 November 1975 and became quasi-stationary near 6°N - 143°E. As indicated in the best track shown in Fig. 8, June began to move northward on the 18th. On the 19th June reached maximum intensity with winds of 160 knots and began to track north-northwest. June continued moving north-northwest until recurving to the northeast on the 22nd (Annual Typhoon Report, 1975). The TCM initiated with the original 00GMT 18 November 1975 data failed to indicate the initial northward progression of June, but predicted instead a west-northwest track. This forecast track is shown with the best track in Fig. 8. Because the original TCM forecast was so poor, this case was of special interest and was studied in detail.

The predominately westward track forecast by the TCM is easily explained when the wind fields used to initiate the model are inspected. The original 250-, 550-, and 850-mb wind fields are shown in Figs. 3, 9, and 10 respectively. The 00GMT 18 November 1975 typhoon warning position

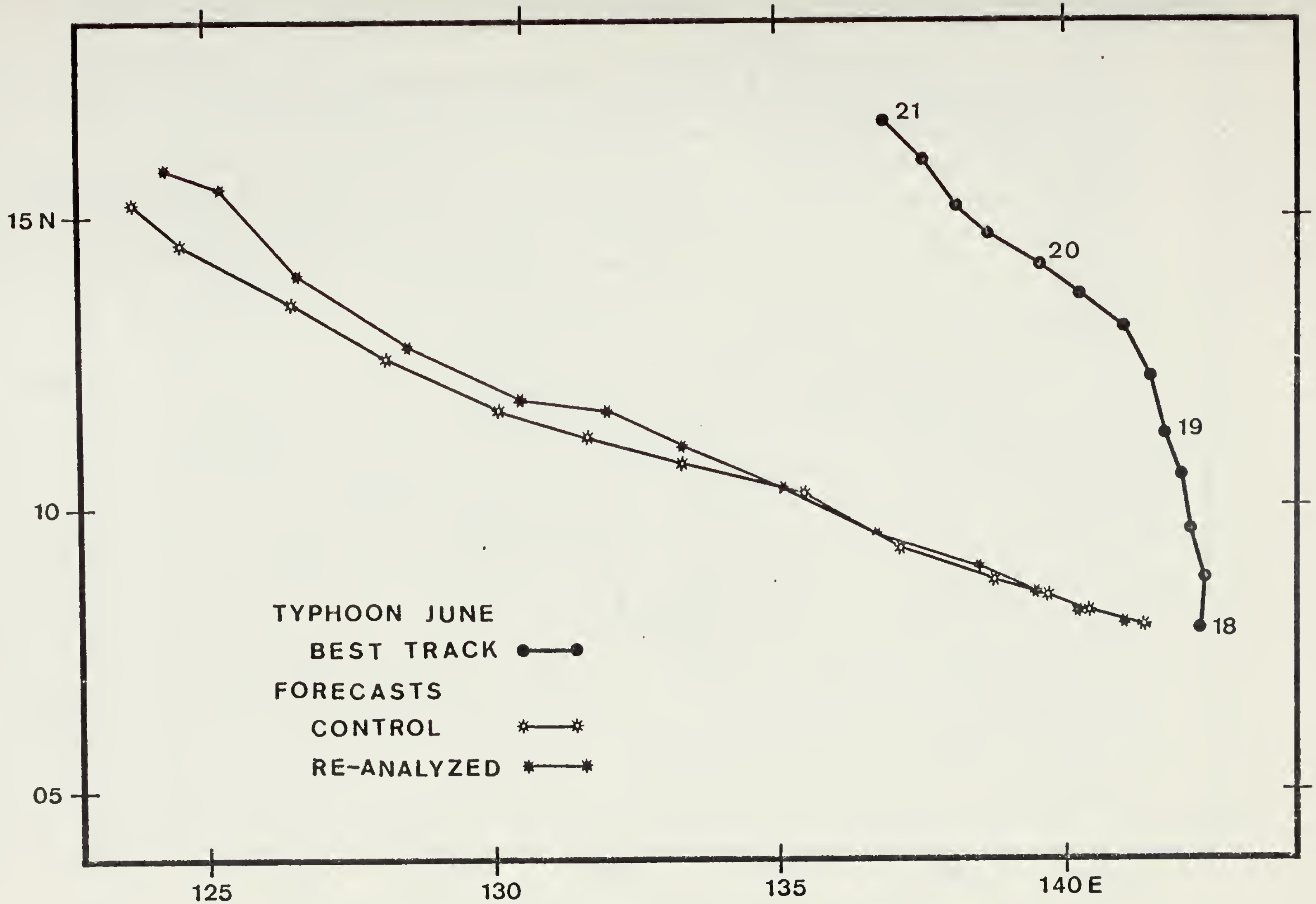

Fig. 8. Comparison of Best track with forecast tracks based on original and re-analyzed wind fields for Typhoon June, 00GMT 18 November 1975.

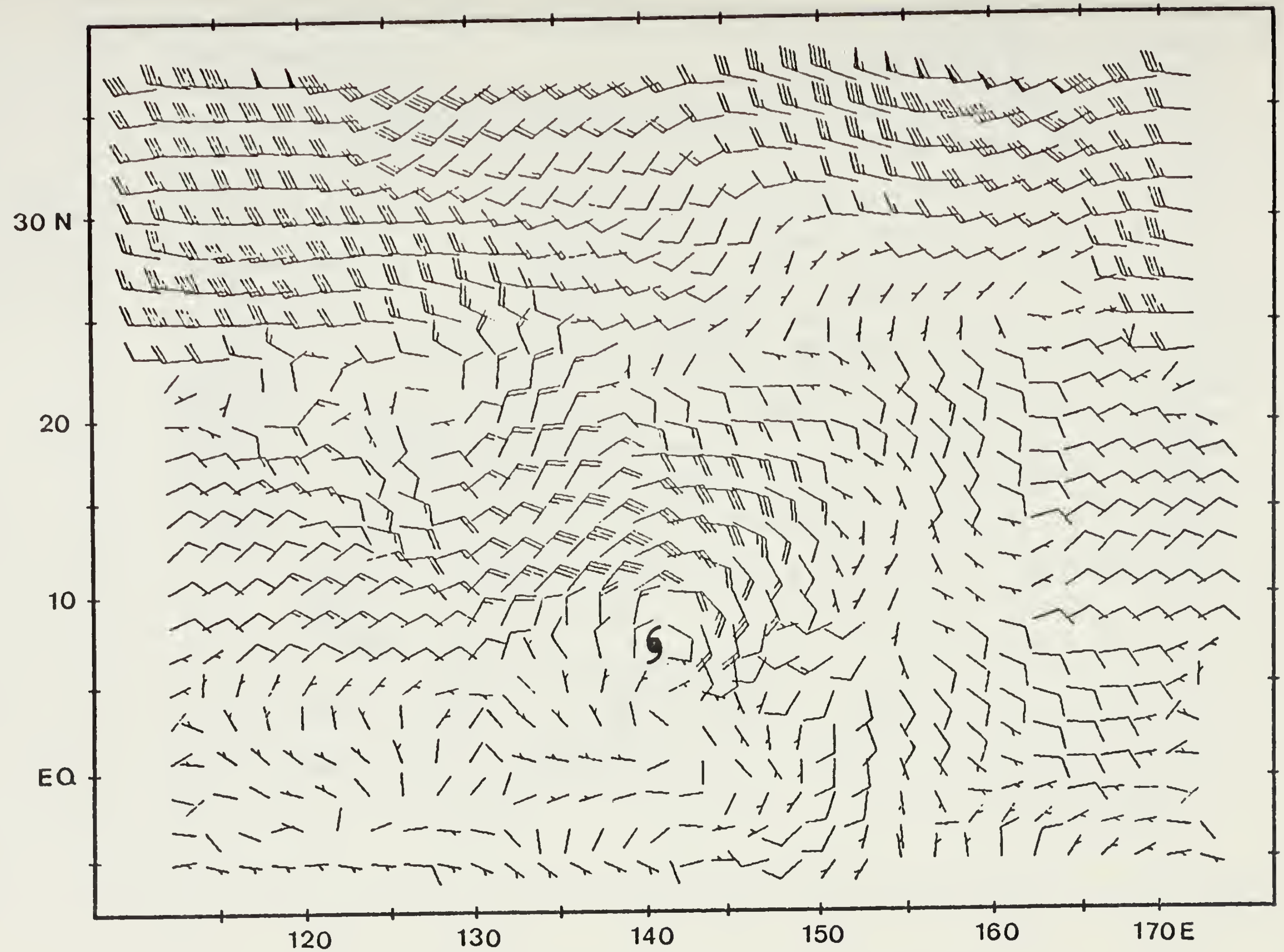

Fig. 9. Original 550-mb wind field for Typhoon June, 00GMT 18 November 1975.

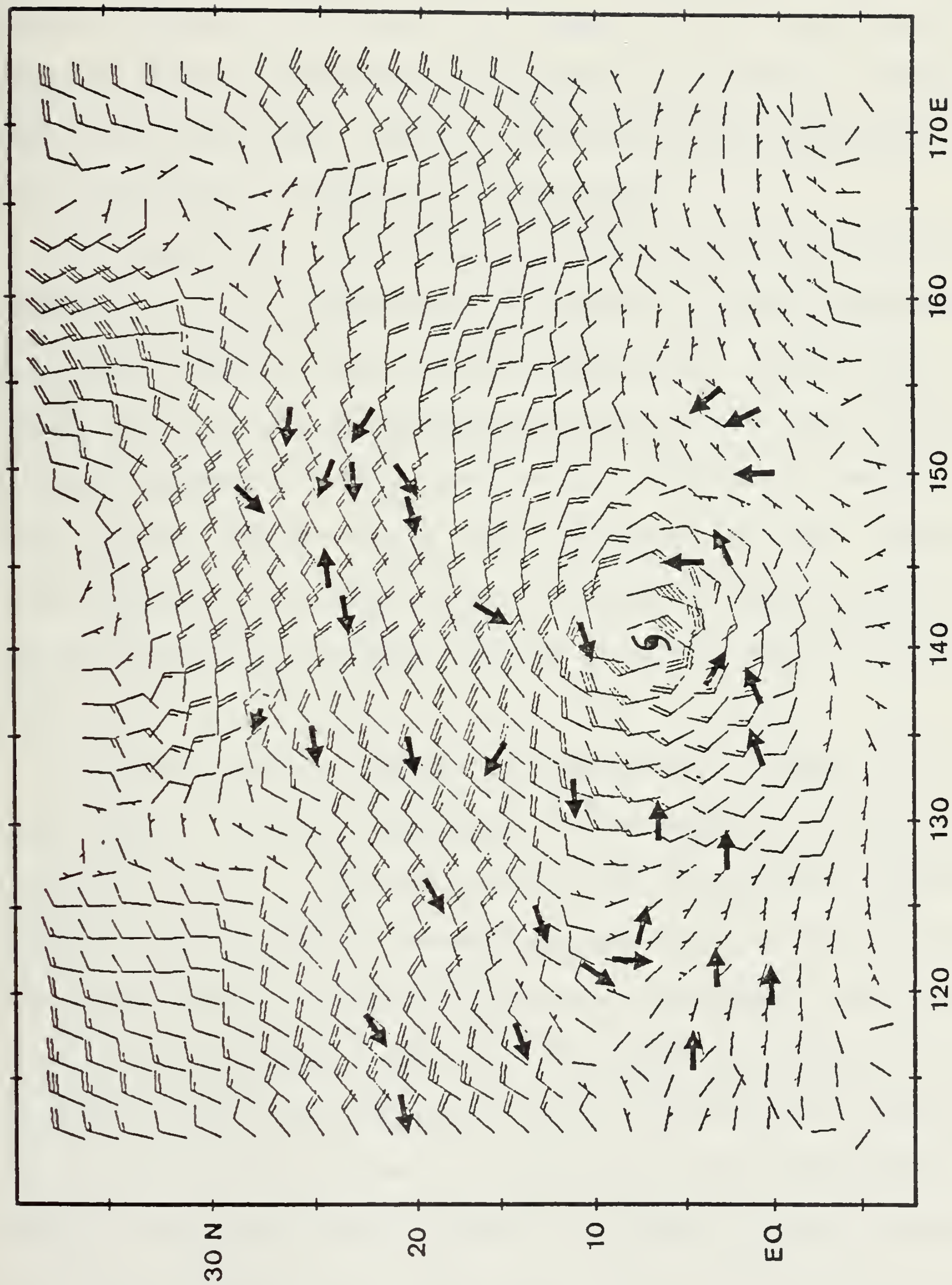

Fig. 10. Same as Fig. 3 except for 850 mb.

is indicated on each figure. The bogused typhoon circulation is clearly evident in the 850-mb wind field. This circulation decreases significantly in the 550-mb field and is not represented at 250 mb. The initial forecast movement of the cyclone is a result of the strong easterly component of the flow just north of the typhoon at all levels. The only winds which would tend to create an initial northward displacement appear east of the storm's location in the 250-mb flow.

The 31 upper-level and 37 lower-level DMSP wind direction estimates which fell within the domain of the TCM for the 18th are superimposed on the original fields in Figs. 3 and 10 respectively. As previously discussed, there are large discrepancies between the GBUA winds and the direction estimates at 250 mb for this case. The 850-mb direction estimates, however, appear to agree more closely with the GBUA. Consequently the re-analysis of the GBUA fields should produce large alterations to the 250-mb wind field, without resulting in major changes to the lower levels.

All re-analyses presented for this case are the results of the original wind component correction techniques. The re-analyzed 850-mb wind field is shown in Fig. 11. The result of inserting the DMSP wind direction estimates into the GBUA has embedded Typhoon June in a basically zonal flow at this level. A vector subtraction of the original GBUA winds from those of the re-analyzed field yields a quantitative measure of the changes at each grid point. The change field for the 850-mb level is shown in Fig. 12. The length of the arrows are proportional to the magnitude of the changes. This change field indicates an increased northward component of the winds throughout most of the region. Except for those west of the typhoon, the change vectors are predominantly weak.

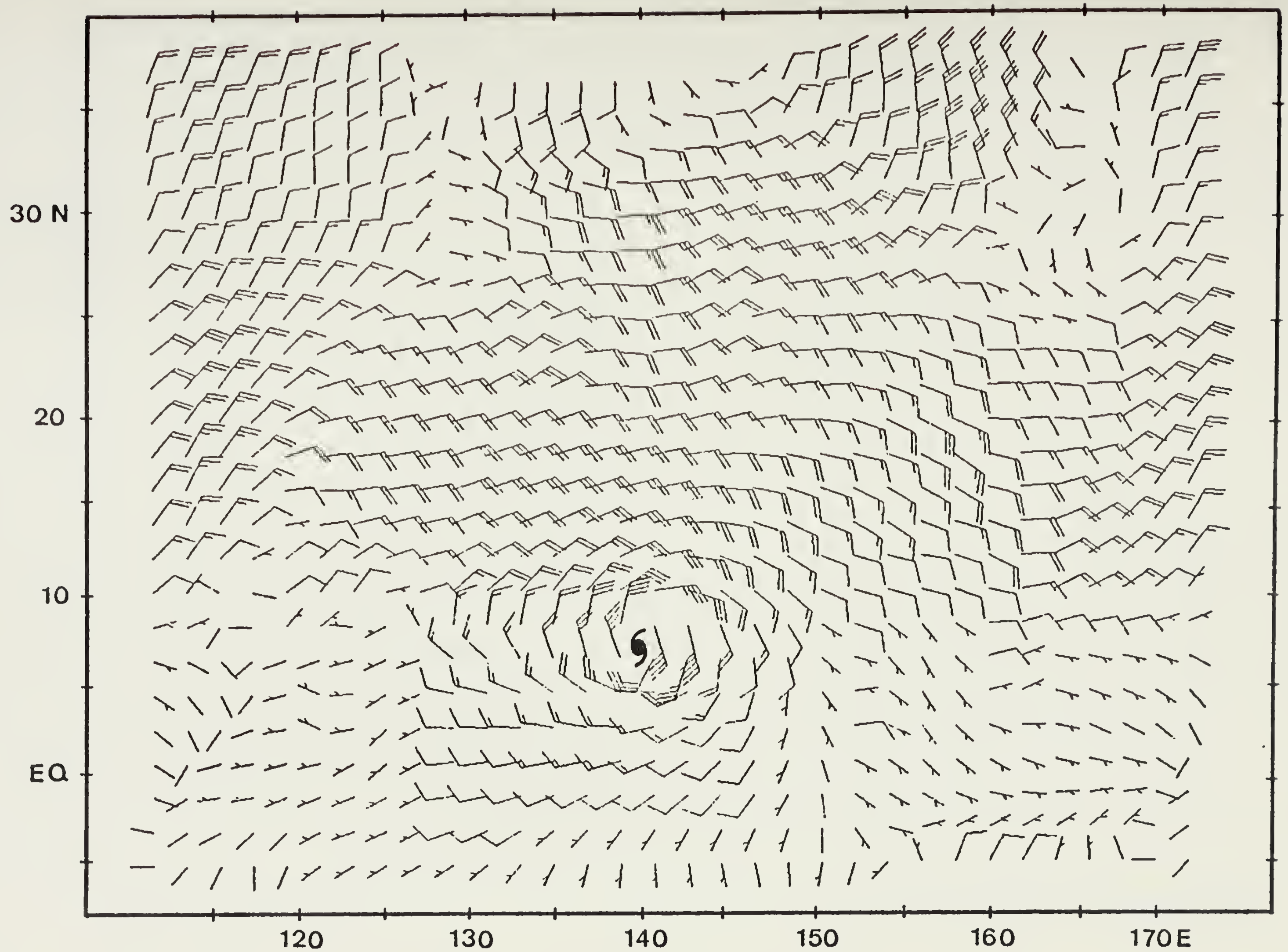

Fig. 11. Result of incorporating 37 DMSP direction estimates into 850-mb wind field shown in Fig. 10.

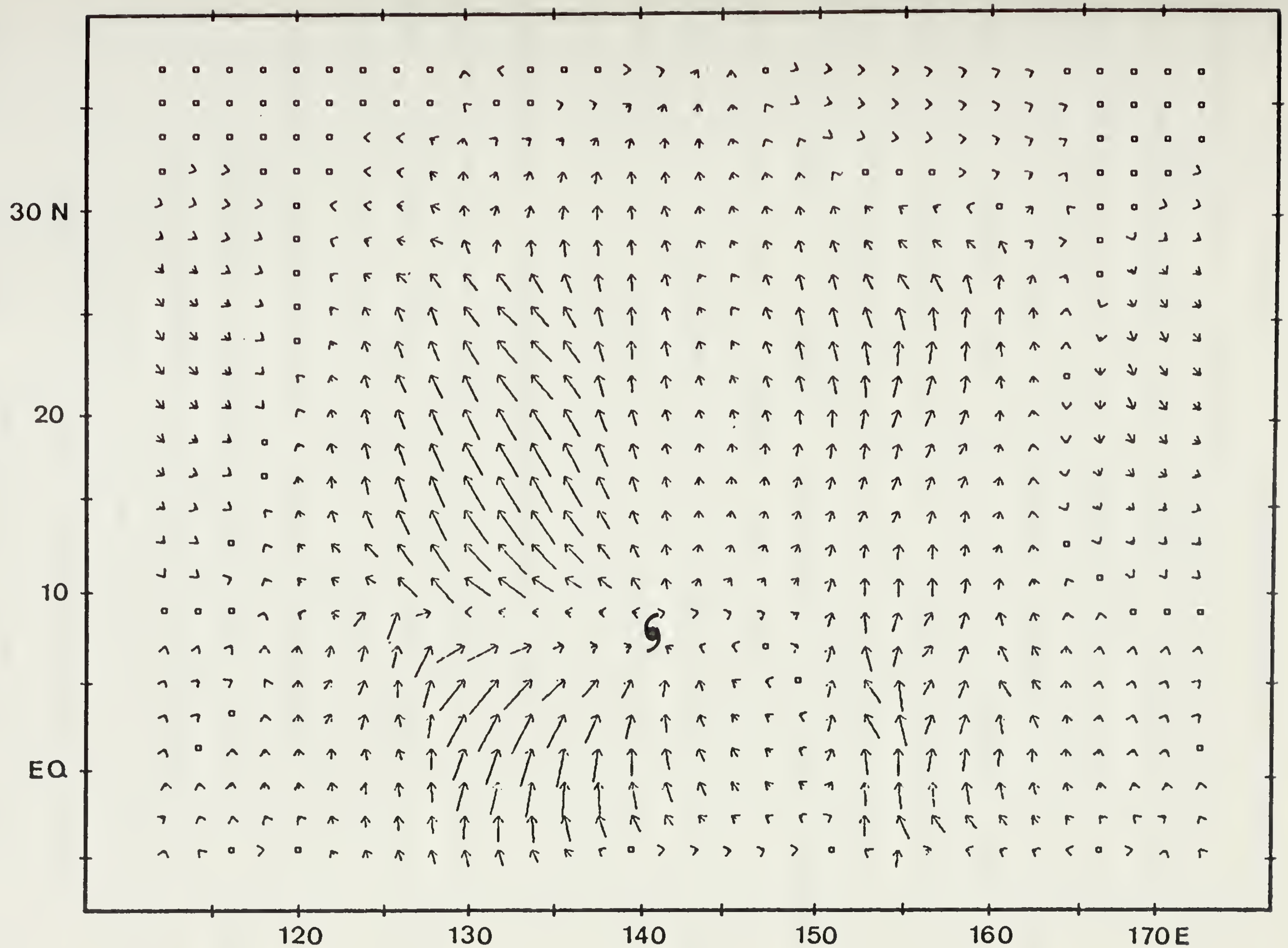

Fig. 12. Changes made in the 850-mb wind field (Fig. 10) due to re-analysis with DMSP direction estimates. Arrow 1 cm long represents a change vector of 9 m/s.

The re-analysis of the 250-mb wind field develops a weak anticyclone centered north-northwest of Typhoon June (see Fig. 6). An evaluation of the 250-mb change field, shown in Fig. 13, reveals that the re-analysis increases the anticyclonic flow around the typhoon and results in a strong northward component of the 250-mb winds west of the initial storm position. The 250-mb non-divergent wind field (Fig. 14) computed during the diagnostic phase of the model is an example of the circulation used by the TCM for the determination of the balanced geopotential fields and for the initial prognostic step. As pointed out by Shewchuk (1977), the significant differences between Fig. 3 (original 250-mb wind field) and Fig. 14 (non-divergent 250-mb wind field) are effects induced by the boundary conditions of the TCM. Comparison of the non-divergent wind field calculated from the original GBUA winds (Fig. 14) and the non-divergent wind field determined from the re-analyzed GBUA (Fig. 15) reveals the effects of the re-analysis on the fields actually used in the prognostic stage of the model. The major effect of the re-analysis is the southeast shift of the anticyclone located at 18°N - 129°E in Fig. 14. This shift eliminates the weak cyclone southwest of the typhoon's position. The overall result of this shift is the increase of the upper-level anticyclonic flow about the typhoon. A small increase occurs in the northwesterly component of the wind over the typhoon with strong increases in the southwest wind components farther west. This result is emphasized in the 250-mb non-divergent wind change field represented in Fig. 16. This change field is simply a smoothed version of the changes produced by the re-analysis of the original 250-mb wind field (see Fig. 13). The major point revealed by a comparison of the two change fields is that the magnitude of all changes is reduced during the determination of the

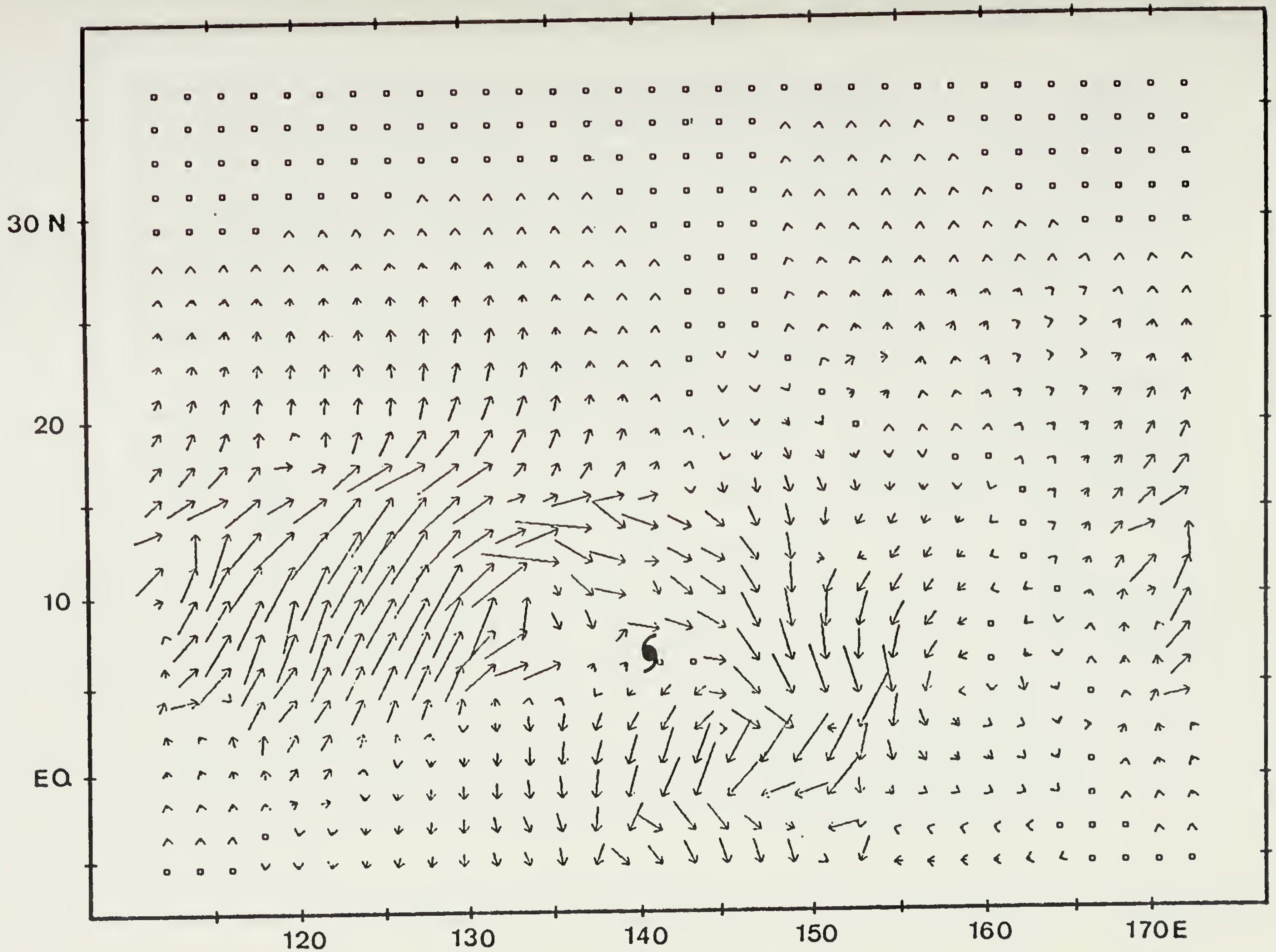

Fig. 13. Same as Fig. 12 except changes made in 250-mb winds in Fig. 3.

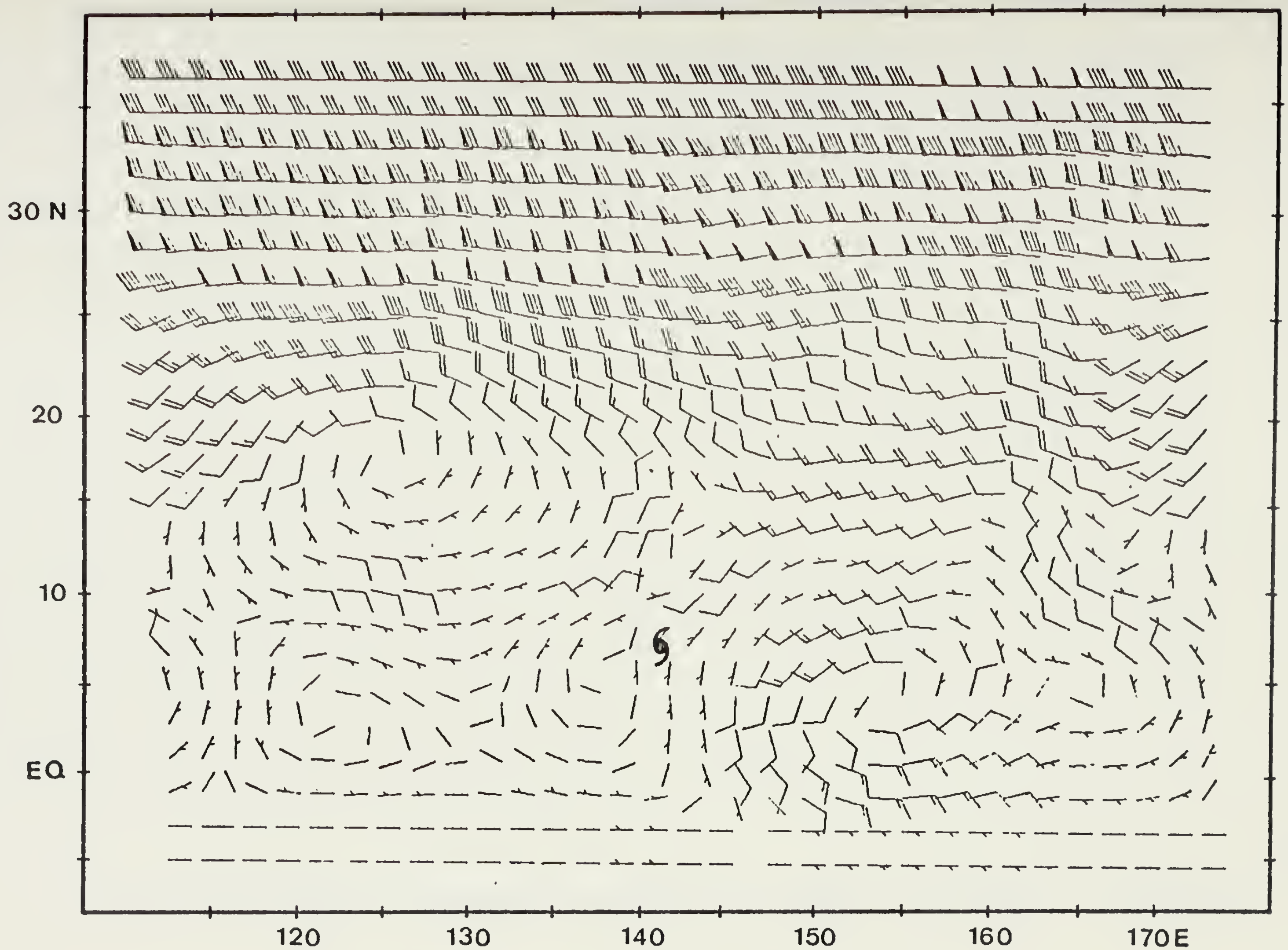

Fig. 14. Non-divergent winds at 250 mb for same field as in Fig. 3.

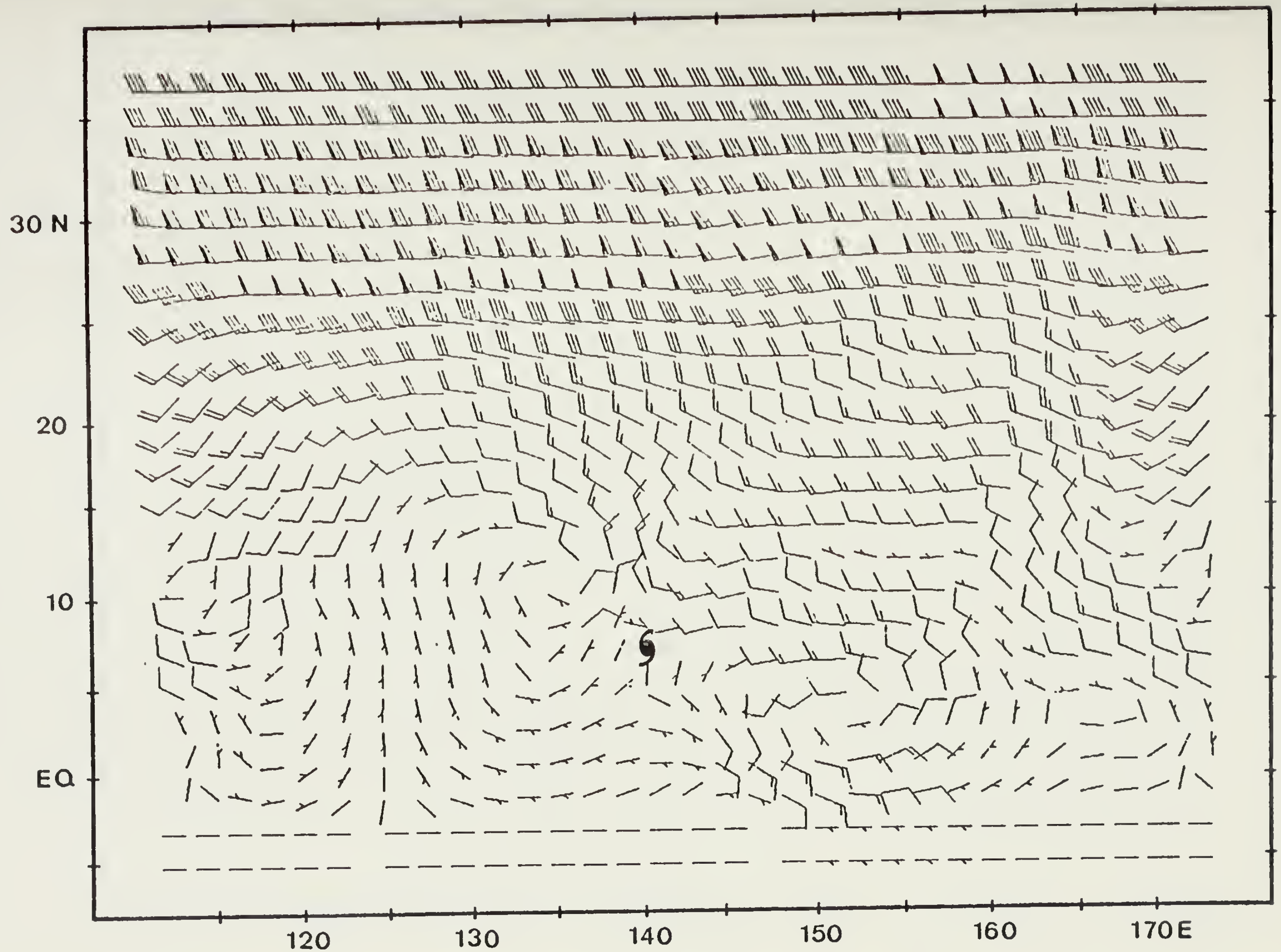

Fig. 15. Non-divergent winds at 250 mb for same field as in Fig. 6.

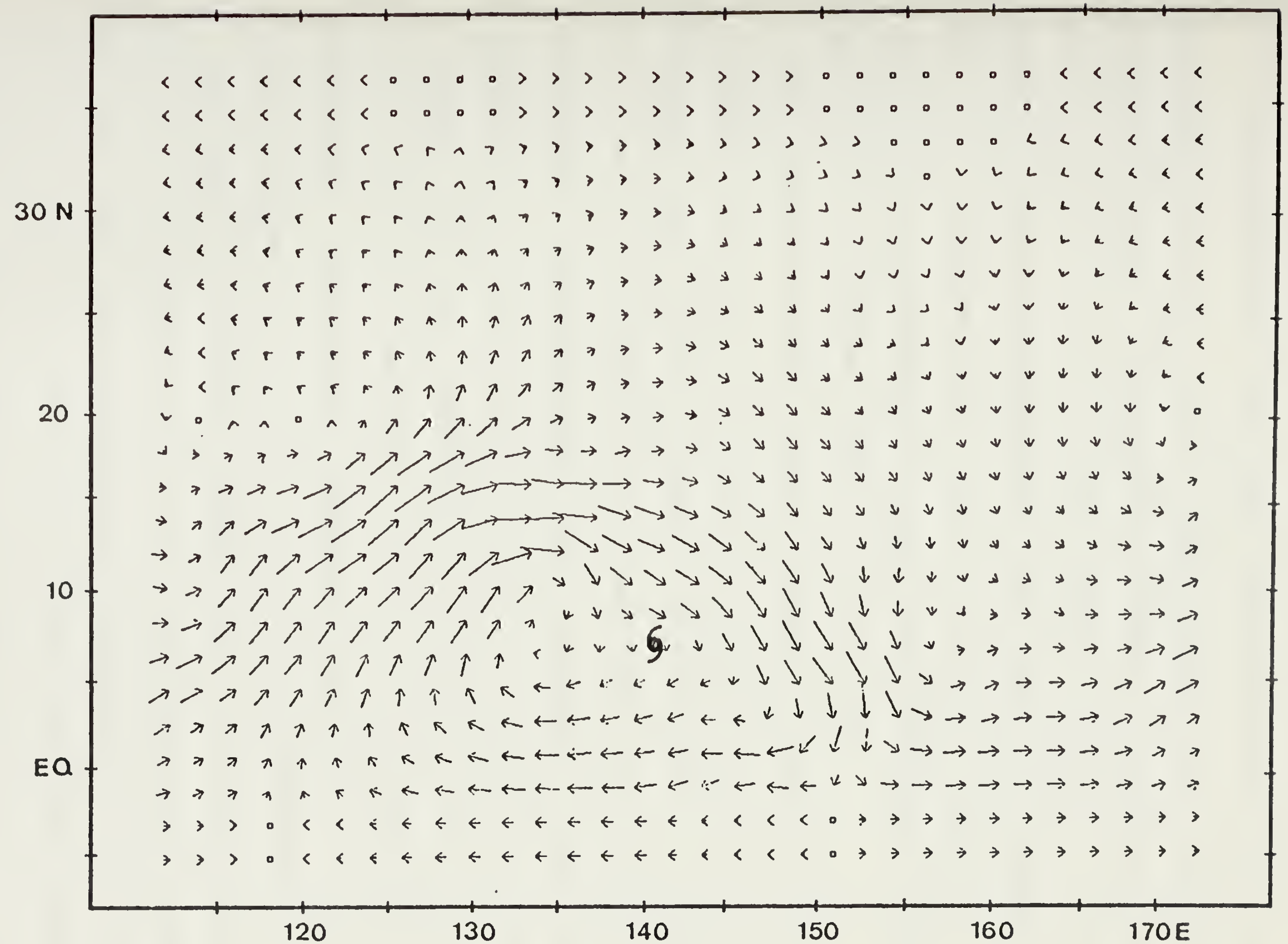

Fig. 16. Changes made in 250-mb non-divergent winds (Fig. 6) due to re-analysis of 250-mb winds with 31 DMSP direction estimates.

non-divergent wind components. Consequently, any favorable changes resulting from a re-analysis of the GBUA fields are reduced prior to the prognostic stage of the TCM.

A close comparison of the original 550-mb wind field (Fig. 9) and the re-analyzed field shown in Fig. 17 indicates only minimal changes to the circulation features. The anticyclone northwest of Typhoon June has been shifted one grid interval to the east; however, this did not result in a significant change in the winds which affect the initial movement of the storm. It is important to note that no new data were available at this level and that the re-analysis was based upon extrapolations of changes made during the re-analyses of upper and lower levels.

The re-analysis of the original fields used to initialize the TCM for Typhoon June results in an increased northward component of the winds throughout a major portion of the upper- and lower-level wind fields. This is the type of change desired to steer Typhoon June northward rather than westward. Unfortunately the largest increases in northward wind components are not in the immediate vicinity of the typhoon but are far to the west. The lack of improvement in the flow near the storm is a result of the lack of observations and the use of the exponential background weight. The storm track forecast by the TCM using the re-analyzed fields is compared with the best track and original TCM forecast in Fig. 8. The errors in the position forecasts based on the original GBUA fields and those in the forecasts based on the re-analyzed fields are shown in Table III. Small errors associated with discrepancies in the initial positioning of the storm are subtracted from all statistics presented. No significant change is observed in the first 30 hours of the forecast. By the 36th hour, however, the typhoon moves into the region of maximum

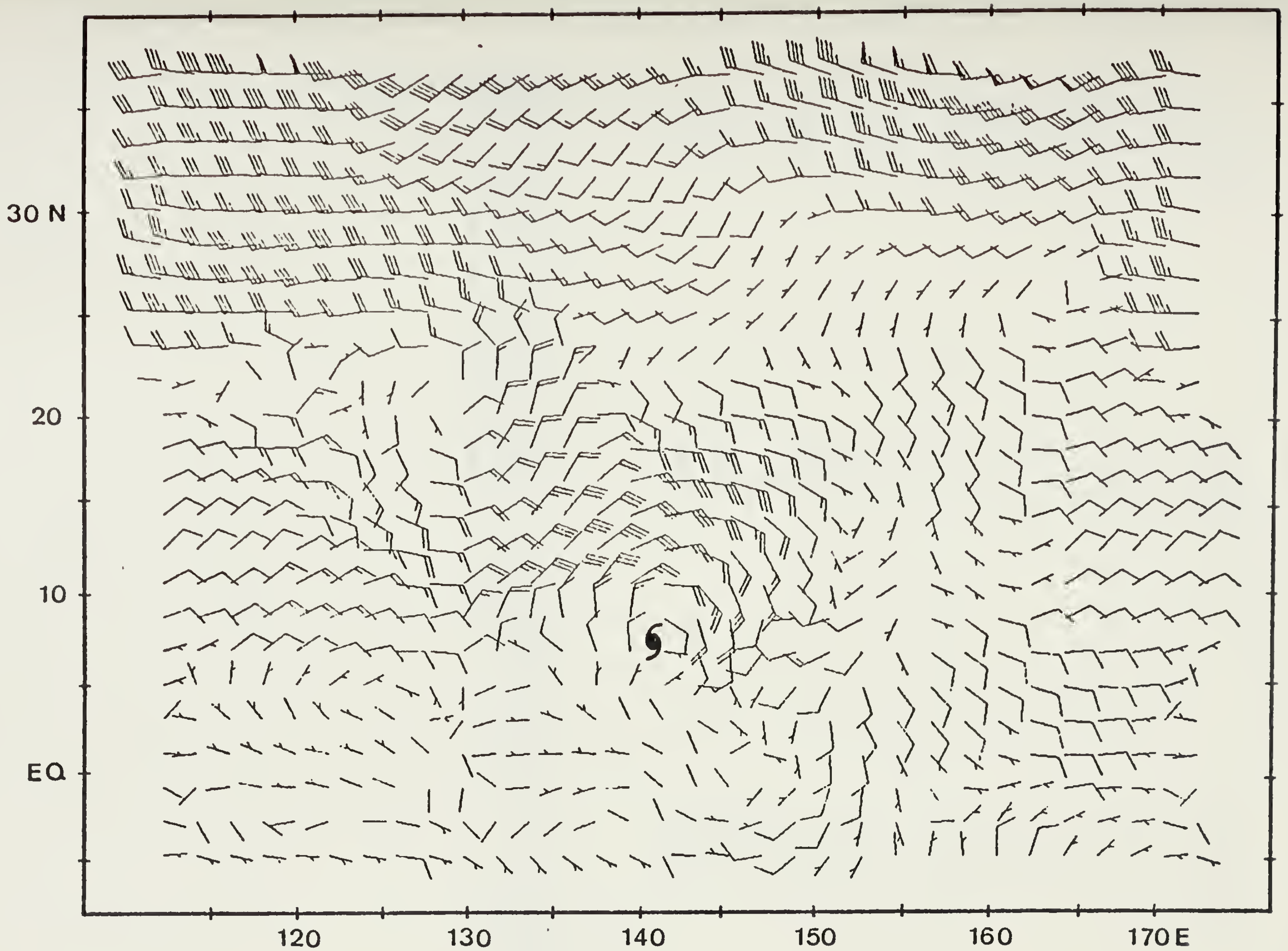

Fig. 17. Re-analyzed winds at 550-mb for same field as in Fig. 9.

TABLE III

Forecast	Original	Re-analyzed
06 hr	128	119
12 hr	212	205
18 hr	315	317
24 hr	452	456
30 hr	602	598
36 hr	775	736
42 hr	873	807
48 hr	967	898
54 hr	1069	998
60 hr	1168	1117
66 hr	1306	1167
72 hr	1300	1208

6-hourly position errors (km) for forecasts based on original GBUA fields and on re-analyzed fields for Typhoon June with an initial time of 00GMT 18 November 1975. The error at each 6-h interval is normalized by the initial position error.

change caused by the GBUA re-analysis. The large increase in the northward component of the winds in this area steers June north of the original TCM forecast positions (see Fig. 8). The track forecast by the model when initiated with the re-analyzed fields does not represent a good forecast; however, the errors shown in Table III do indicate the forecast improvement due to the re-analysis. These statistics reveal an average 75 km improvement in the forecast positions for 36 hours and later.

B. TYPHOON ELSIE

The second case presented is the TCM forecast for Typhoon Elsie initiated with the 00GMT 13 October 1975 data. The results of this case are presented because of the major improvement in the forecast caused by the re-analysis of the GBUA fields. The original TCM forecast track and the track forecast after the re-analysis of the GBUA are compared with the best track positions in Fig. 18. After entering the South China Sea on 12 October 1975, Elsie tracked due west passing 35 nm south of Hong Kong on the 14th. Continuing westward, Elsie made landfall on the southern China coast at approximately 1500GMT on the 14th (Annual Typhoon Report, 1975). The best track positions are available only through 00GMT 15 October 1975 due to the rapid dissipation of Elsie after landfall. Positions forecast by the TCM for times after 00GMT on the 15th are shown in Fig. 18 to indicate the directional tendency of the forecasts. The TCM initiated with the original GBUA fields forecast a northward recurvature of Elsie along the China coast. Such a forecast could have resulted in disastrous consequences for the inhabitants of Hong Kong. It is clear that the TCM initiated with the re-analyzed GBUA fields gave a far superior forecast for the movement of Elsie. Although the forecast speed is much too slow during the first 36 hours, the use of the updated GBUA fields results in a good direction forecast.

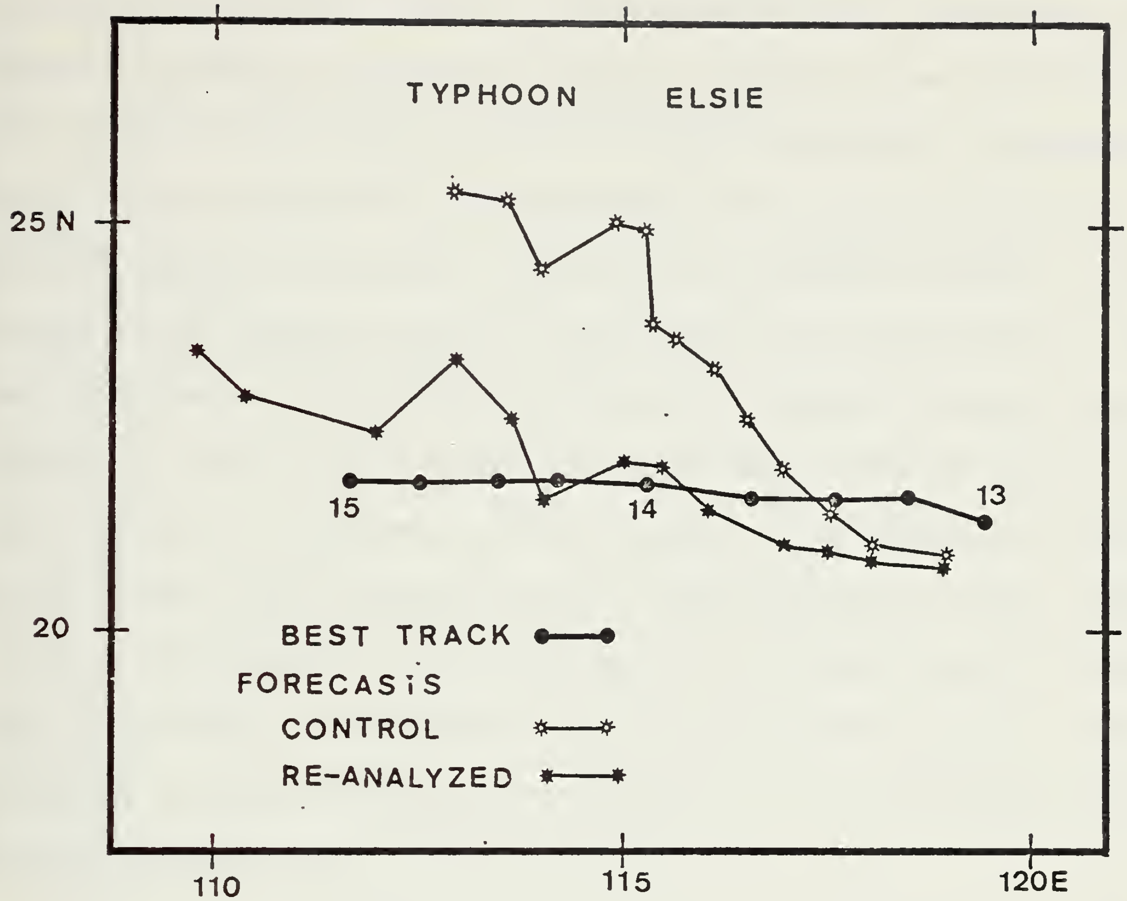

Fig. 18. Same as Fig. 8 except for Typhoon Elsie, 00GMT 13 October 1975.

The original 850- and 250-mb wind fields with DMSP direction estimates superimposed are shown in Figs. 19 and 20 respectively. The original wind component corrections technique was used to re-analyze these fields with 10 upper-level and 9 lower-level DMSP direction estimates. The improved forecast can be explained by an examination of the change fields which resulted from the re-analyses. At 850 mb the re-analysis results in weak changes in the immediate vicinity of the storm which would impede an initial west or northwest storm movement (see Fig. 21). Similar, but much larger changes are shown in the corresponding 250-mb change field (Fig. 22). The large changes near the storm occurred in spite of the exponential background weight, which indicates that the original 250-mb wind field simply failed to define the circulation represented by the DMSP direction estimates. The changes made in the immediate vicinity of the typhoon prevented the previously forecast recurvature and resulted in a 227 km decrease of the 48-hour forecast error.

C. 1975 RESULTS

The model initiated with fields re-analyzed using the original wind component corrections scheme was run for 32 western Pacific typhoons. These typhoons are listed with the number of direction estimates available at each level in Table I. A comparison of the forecast errors produced by the model when initiated with the original GBUA fields (control cases) and when initiated with the re-analyzed fields indicates the relative improvement which results from the re-analyses. The average forecast position errors for the 32 cases tested are shown in Table IV. The number of forecasts which equalled or showed improvement over the control cases are also tabulated for each six-hourly forecast interval. In spite of the improvements in the forecasts presented for Typhoons June and Elsie, it is

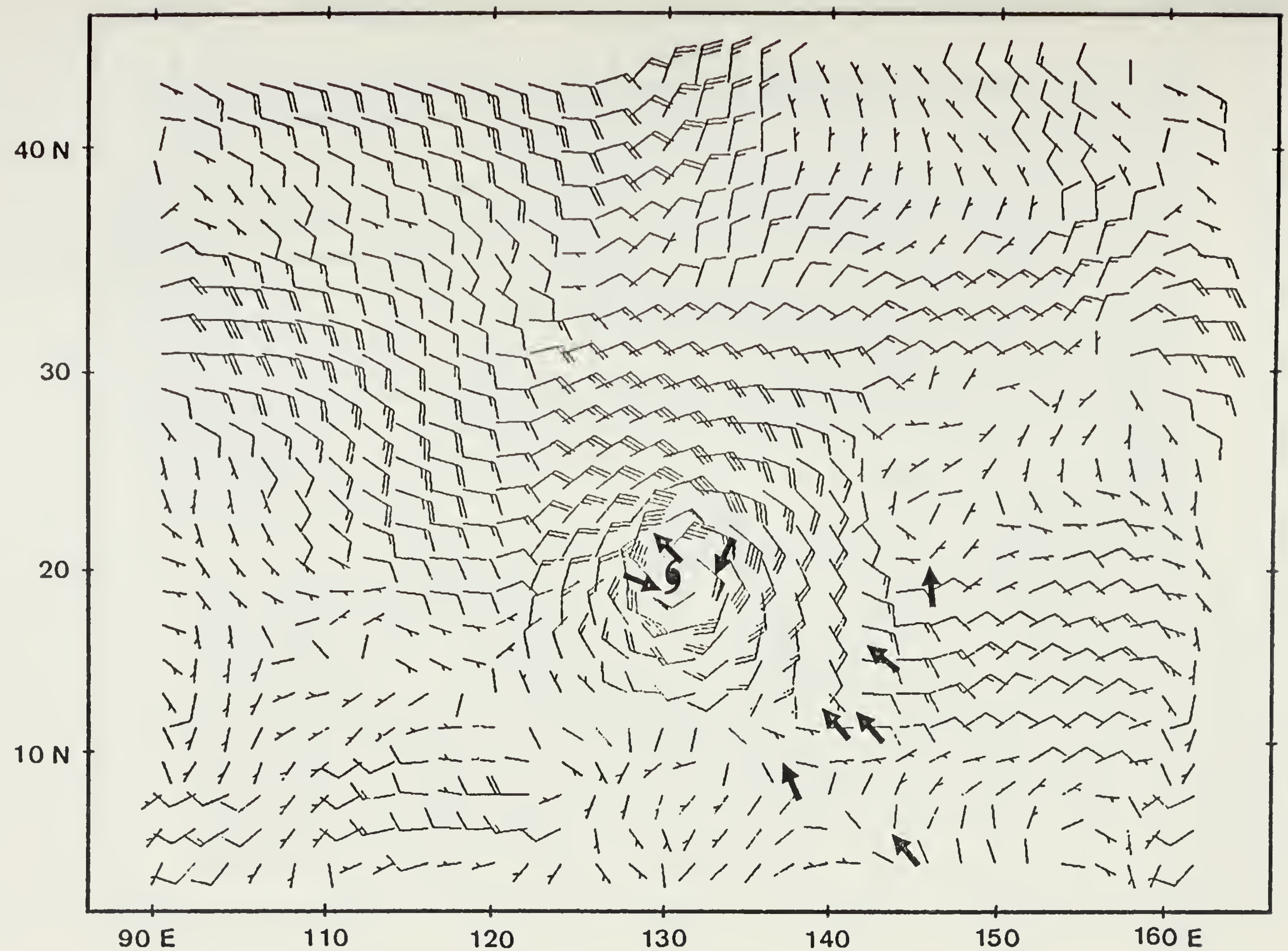

Fig. 19. Original 850-mb wind field and DMSP wind direction estimates (→) for Typhoon Elsie, 13 October 1975.

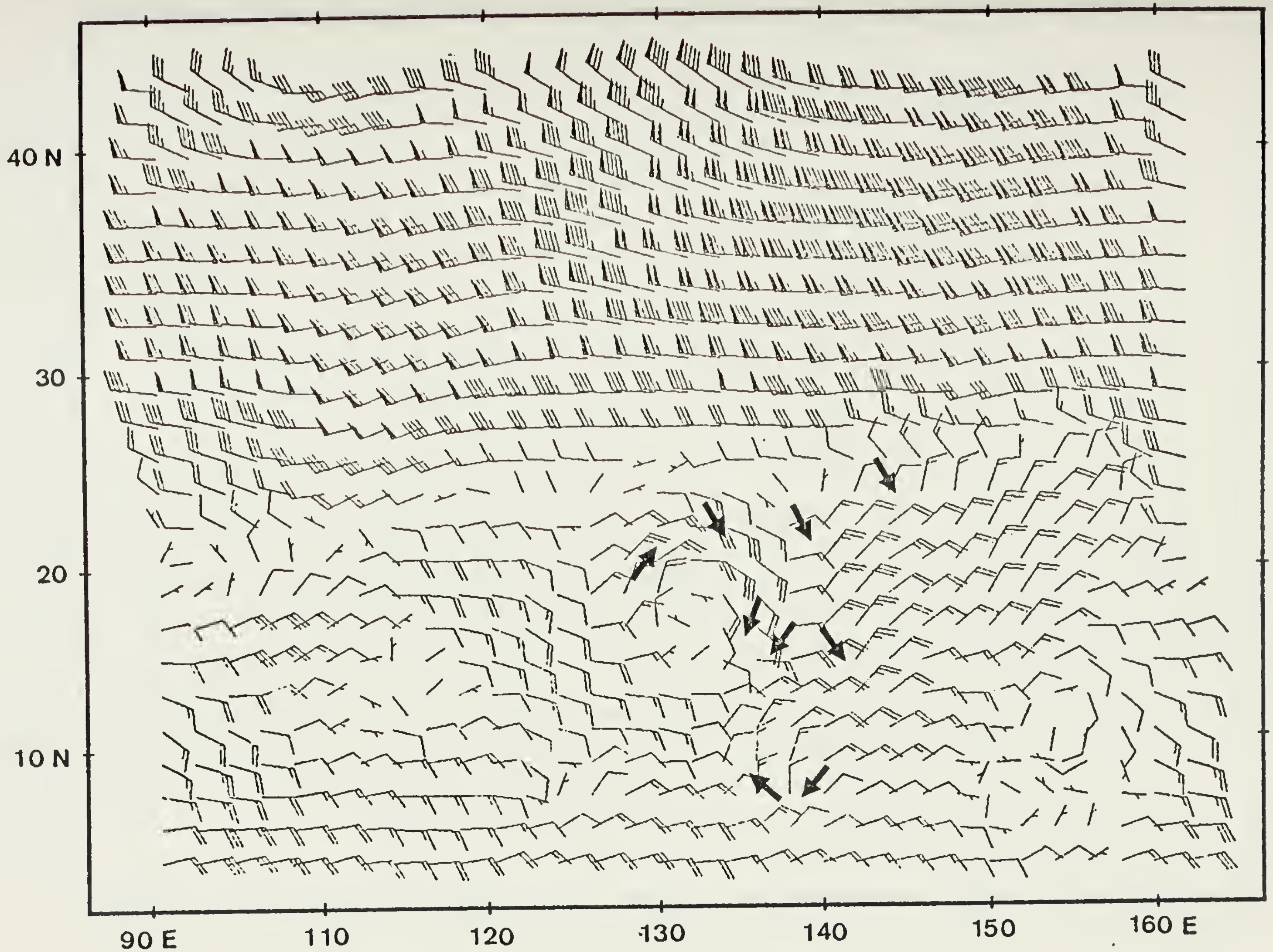

Fig. 20. Same as Fig. 19 except for 250 mb.

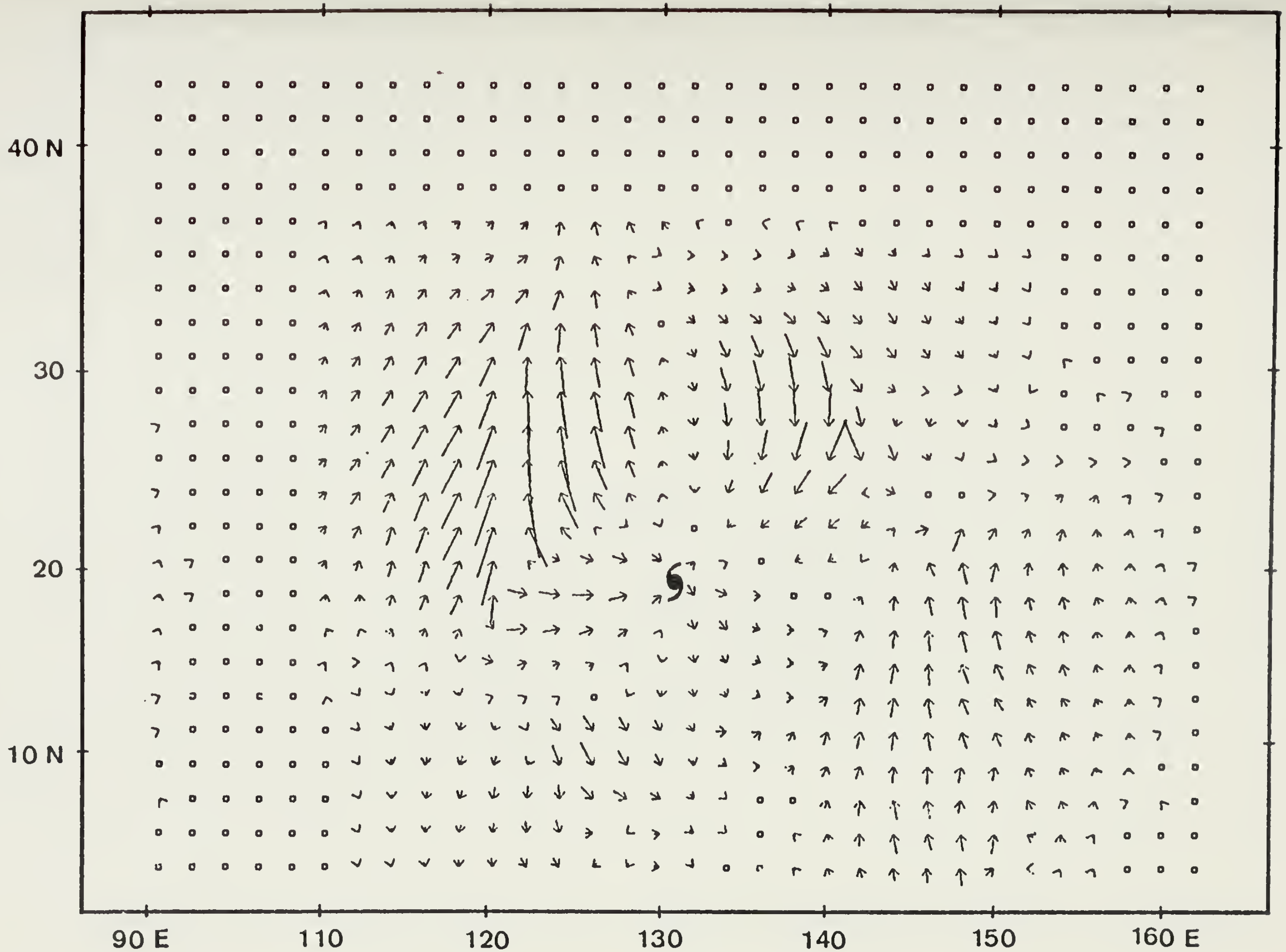

Fig. 21. Changes made in the original 250-mb wind field in Fig. 19 by the incorporation of 10 DMSP direction estimates.

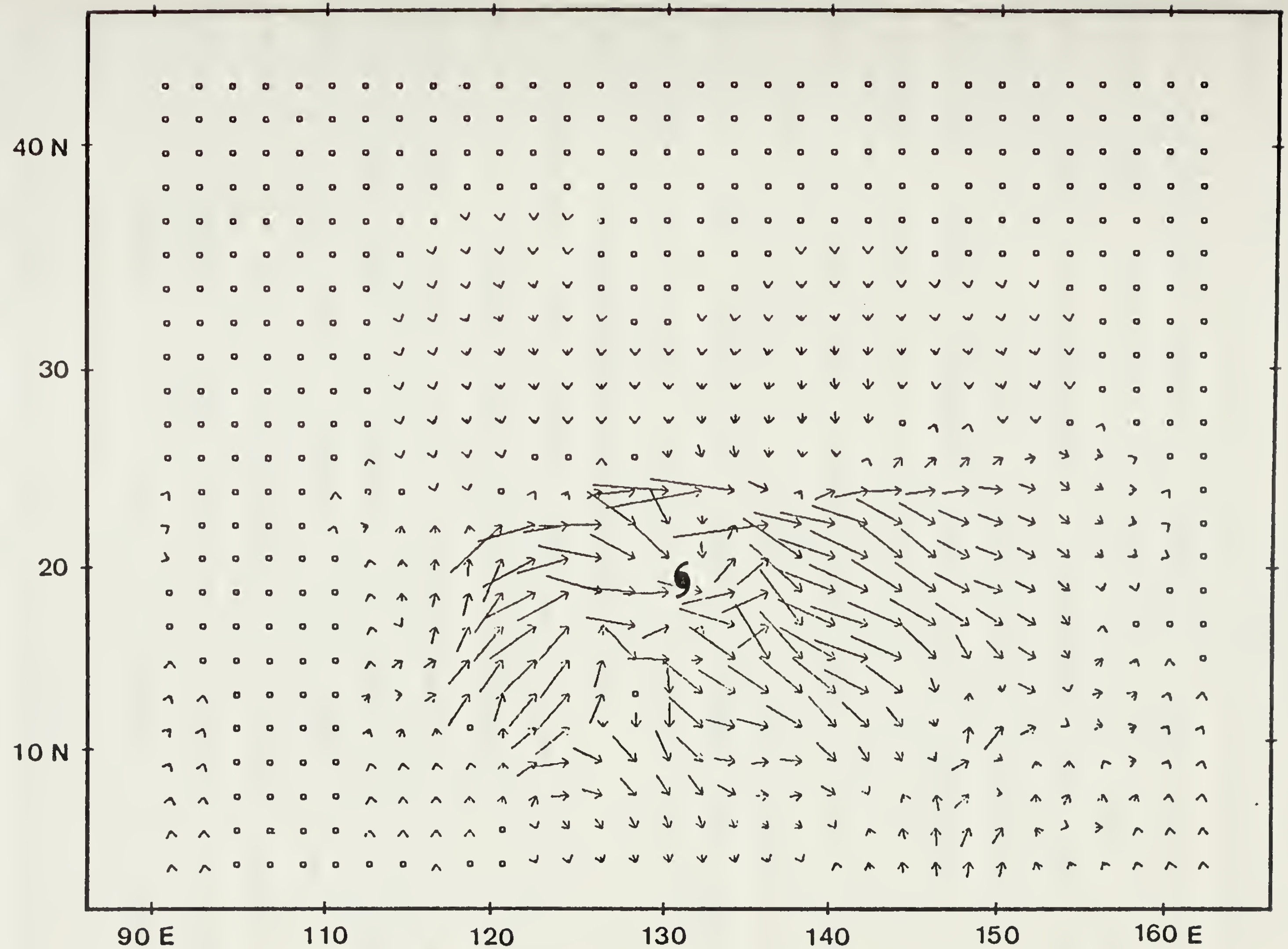

Fig. 22. Changes made in the original 250-mb wind field in Fig. 20 by the incorporation of 9 DMSP direction estimates.

apparent from Table IV that the re-analyses with the available DMSP wind direction estimates failed to improve the seasonal results. In fact, the re-analyzed fields increased the average error in some cases by as much as 5%. For all forecast intervals, only 45% of the forecasts based on re-analyzed fields equalled or improved the tracks forecast in the control cases. The re-analyses of the initial fields result in only minor changes in the forecast positions of the majority of the cases. The separation between the control case positions and those forecast by the model when initiated with updated fields was never greater than 300 km and usually less than 150 km. Notable forecast differences occur only when the re-analyses result in significant changes in the wind fields in the immediate vicinity of the typhoon or in areas into which the typhoon eventually tracks. The effective changes of the GBUA winds produced by the re-analyses for most cases were small due to both the limited number of direction estimates available and their location.

An evaluation of the forecast tracks based on the re-analyzed fields reveals that no inherent directional bias is produced by the objective analysis scheme. That is, almost an equal number of cases exist where the re-analyses result in a steering to the left of the control case tracks as do cases where the steering is to the right. Elsberry (1977) indicated a bias toward slow displacements in the tracks forecast by the TCM. The introduction of DMSP wind direction estimates into the GBUA wind fields increases this bias early in the forecast. The rates of displacement forecast for the majority of the re-analyzed cases were slower than the corresponding forecasts made by the control cases during the first 30 hours of the forecast. This decrease in displacement speed is apparently a result of changes in the original wind fields which tend

TABLE IV

Forecast	I	II	Error Original	Re-analyzed
6 hr	32	20	86	84
12 hr	32	18	142	145
18 hr	31	14	204	204
24 hr	31	13	263	260
30 hr	29	13	335	331
36 hr	27	10	397	405
42 hr	22	7	408	410
48 hr	20	8	451	446
54 hr	18	9	528	541
60 hr	16	5	571	612
66 hr	9	3	652	681
72 hr	9	5	739	750

Mean 6-hourly position errors (km) for forecasts based on original GBUA fields and on re-analyzed fields for the 32 cases tested. Also tabulated are the number of forecasts (I) for each 6-h interval and the number of forecasts (II) based on re-analyzed fields which equalled or showed improvement over the forecasts based on the original GBUA fields.

to impede the initial motion of the storm. In almost all cases the rates of displacement increase during the later intervals of the forecast period.

It is interesting to note that the smallest changes in forecast tracks were for typhoons for which only 250-mb DMSP direction estimates were available. There are two probable reasons for the minimal forecast track changes for these cases. The first is model related. As shown in the comparison of the 250-mb wind field and the 250-mb non-divergent wind field for Typhoon June, the calculation of the non-divergent winds can result in significant alterations to circulation features as well as reducing the magnitude of the re-analysis-induced changes. The second reason is a result of the location of the direction estimates. The 250-mb wind direction estimates are based on cirrus streamers which are mostly located in the typhoon outflow and are, therefore, removed from the immediate vicinity of the vortex center. Consequently most changes produced by the re-analysis of the 250-mb wind fields are not only too distant to affect the immediate motion of the storm, but also are reduced prior to the prognostic stage of the TCM. These facts, combined with the absence of changes in the 850-mb wind field, explain minimal corrections to the forecast storm tracks.

Of the 32 cases initiated with the re-analyzed GBUA wind fields, two forecasts terminated 6 hours earlier than the forecasts when the model was initiated with the original GBUA winds. Conversely, the addition of the DMSP wind direction estimates to the GBUA enabled the model to track four storms 6-12 hours longer than was possible in the control cases. In one case, the re-analyzed fields extended the ability of the model to track the storm for an additional 30 hours. In all of these cases the storms

were comparatively weak (< 65 kts), and the explanation of the differences is due to the strengthening/weakening of the bogused vortex during the re-analyses.

Six cases were tested using the objective analysis technique in which a minimum speed of 20 knots was assigned to each DMSP direction estimate prior to re-analyzing the u and v wind components of the first guess fields. The resulting track forecasts for the two cases for which the initial fields were re-analyzed with this technique are labeled as A in Fig. 23. The tracks labeled as B are those based on the fields re-analyzed using the original component correction technique. The control case tracks which were forecast by the TCM initiated with the original GBUA fields are labeled as C. A comparison of these tracks with the best track (D) reveals that the introduction of the 20 knot speed minimum increases the change in the forecast track but does not alter the directional tendency of this change. Track B for the initial time of 00GMT on the 18th shows an improvement over track C during the later forecast intervals. This improvement is increased by the introduction of the 20 kt speed minimum (Track A). Track B for the 00GMT initial time on the 19th indicates larger forecast errors as compared to track C. Once again, the introduction of the 20 kt minimum alters the magnitude of the changes in the forecast track (A), but not the direction in which these changes are made. A forecast improved by the re-analyses of the initial wind fields is improved even more by assuming the 20 kt minimum. Unfortunately, a bad correction in forecast tracks only becomes worse using this technique.

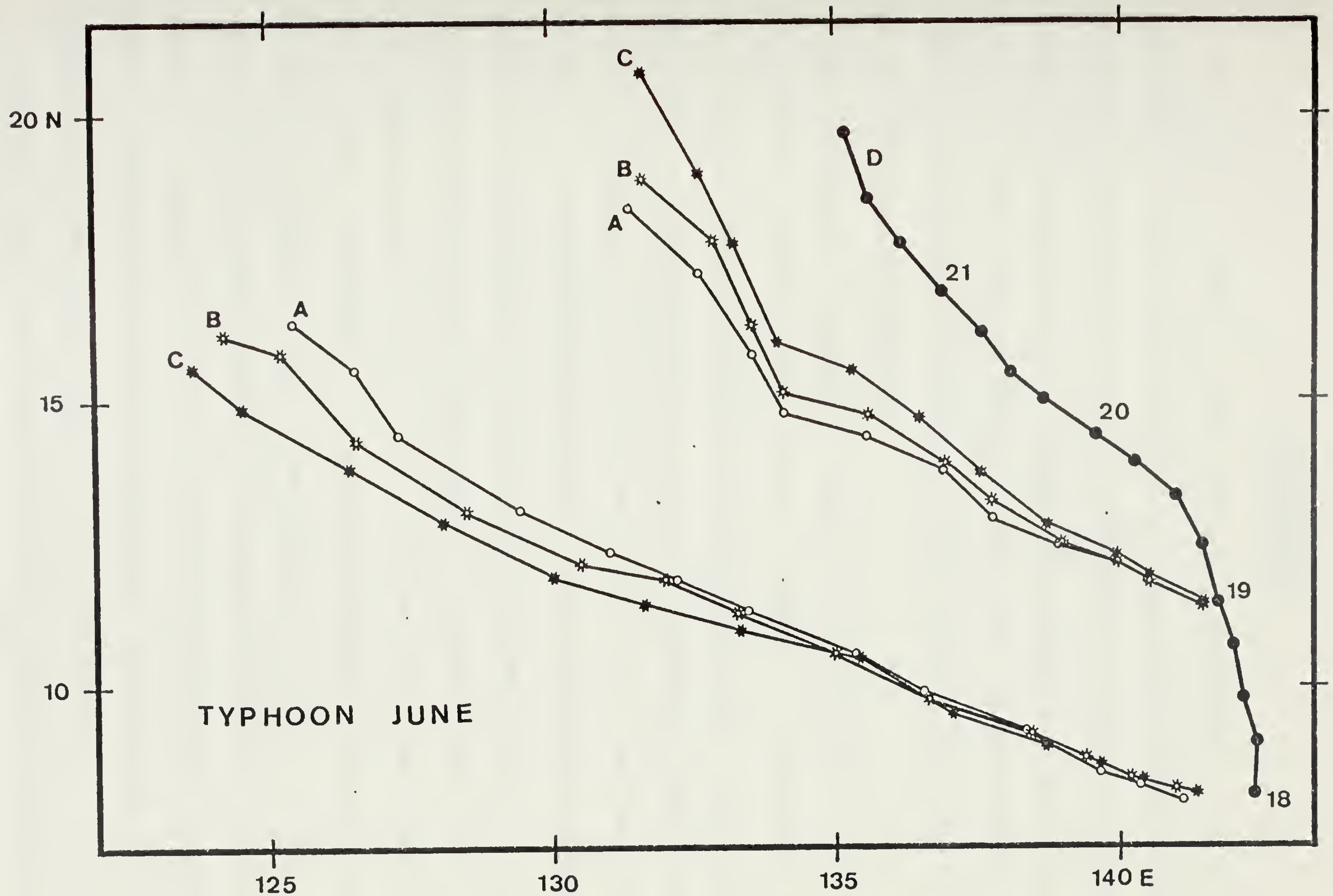

Fig. 23. Forecast tracks for Typhoon June based on re-analyzed fields using DMSP direction estimates with 20 knot minimum speeds (A) compared to those based on fields re-analyzed with the original component scheme (B) and those based on the original GBUA fields (C). Best track is shown as D.

VI. CONCLUSIONS

The primary objective of this research was to demonstrate incremental improvements in storm tracks forecast by a coarse-grid primitive-equation tropical cyclone model due to the incorporation of DMSP wind direction estimates into the data base. A comparison of GBUA wind fields with JTWC analyses and DMSP direction estimates showed that the fields used to initiate the TCM for the 1975 typhoon season were not representative of the environment of the typhoons.

Two variations of a mesoscale objective analysis scheme were evaluated with respect to their ability to improve the input for the model. The first combines DMSP wind direction estimates with speeds interpolated from GBUA fields to yield wind vector estimates. Corrections made to the fields used to initiate the TCM were based on differences between the wind components of the initial fields and those of the wind vector estimates. Assuming a minimum speed of 20 knots to be associated with each upper-level direction estimate created larger changes in forecast tracks, but did not show improvement over the use of the technique with speeds interpolated from the first guess values. In the second approach the wind direction fields were re-analyzed based on the differences between the DMSP wind directions and the GBUA directions at the same locations. This method improves the representation of the structure of the tropical cyclone; however, it fails to accurately represent the large-scale flow in areas of rapidly changing wind directions and minimal observations.

A primary result of the evaluation of the objective analysis scheme was the inability to properly represent circulation features with poorly

distributed DMSP direction estimates. As expected, direction estimates must be located on each side of a circulation feature before it can be represented by an objective analysis technique. DMSP operators aware of this fact can concentrate on making direction estimates throughout an area of interest instead of increasing the density of estimates in limited regions.

The incorporation of DMSP direction estimates into the GBUA failed to improve the seasonal tropical cyclone model track error statistics for 1975. It is difficult to pinpoint any specific reason for this failure. The lack of DMSP direction estimates near the storm and in areas into which the storm eventually tracked resulted in few effective changes during the re-analysis procedure. Improvements which were introduced by the re-analysis of the initial fields were minimized by the model during the reverse-balancing process, and many circulation features were altered due to the boundary conditions of the "channel" model. DMSP direction estimates were added to the data base of the TCM on a case-by-case basis. As such, adjustments made in the wind fields for one initial time did not improve the initial fields for the model for later forecasts. This is in contrast to the 1976 season where the improvement due to the addition of the DMSP direction estimates may have been cumulative. In spite of the lack of improvement in the overall 1975 seasonal results, the forecasts for Typhoons June and Elsie indicate that the addition of the DMSP direction estimates to the data base can result in forecast improvements if the basic current is significantly improved. The DMSP wind direction estimates on the periphery of the storm are not adequate in redirecting the initial basic current. Consequently an arbitrary adjustment in the initial wind fields (Shewchuk and Elsberry, 1978) seems to be required to redirect the initial storm path in the model.

APPENDIX: THE OBJECTIVE ANALYSIS SCHEME

The objective analysis scheme developed by Barnes (1973) was used to incorporate the DMSP wind direction estimates into the GBUA analyses. The scheme is an iterative technique based on the premise that distributions of meteorological variables can be represented by an infinite sum of independent, harmonic waves. Spatial weighting of observations is used to obtain interpolated values at regularly arrayed grid points. The value at each grid point in a first guess field is corrected by a value proportional to the difference between the observation and the first guess at the observation location. This difference is defined by

$$D(i,j) = O(i,j) - F(i,j) \tag{A-1}$$

where D is the difference at point (i,j), O is the observed value, and F is the result of a bilinear interpolation of the first guess field to the observation location. The correction at grid point (i,j) is given by the expression

$$C(i,j) = \frac{\sum_{m=1}^{N} W_m D_m}{\beta + \sum_{m=1}^{N} W_m} \tag{A-2}$$

where C(i,j) is the correction, N is the number of observations that influence the value at (i,j), and W is the weight function. β, an initial weight given the first guess values, is a function of the confidence in the first guess. A high value for β would indicate a high confidence in the first guess field and would result in little change of that field by the insertion of observations.

The weight function, W, insures that the corrections to the first guess values caused by the insertion of an observation decrease as the distance from the observation increases. The weight function for the first pass through the observations is defined by

$$W = \exp(-r^2/K) \tag{A-3}$$

where r is the distance of the observation from the grid points and K is an arbitrary parameter which is dependent upon data distribution and the scale of the specific phenomenon to be represented. The selection of K determines the magnitude of the weight function for a given distance from an observation and thus the response of the resulting weight-averaged field to the initial observations. This response determines the wavelengths of the variables represented by the objective analysis of the observations. The judicious selection of K specifies whether the objective analysis will depict only long wave components or represent short wave features in the data. Barnes' derivation depends upon the existence of a continuum of information concerning the atmospheric variables to be represented. In practice this continuum is never found, thus the smallest resolvable features and the practical lower limit on K are determined by the data distribution.

The addition of the first guess field and corrections computed during an initial pass through the observations yields an updated field which serves as the first guess for the only iteration required by the analysis scheme. Reducing the weight function by introducing a factor γ on the first corrective iteration increases the convergence rate, thus eliminating the need of costly iterations required by similar objective analysis techniques. The weight function on the second pass becomes

$$W = \exp(-r^2/K\gamma) \qquad (A\text{-}4)$$

Barnes shows that an optimum γ lies in the range of 0.2 to 0.4. The final adjusted value at each grid point is the sum of the second pass corrections and the updated first guess field used in their determination.

The procedures described above yield isotropic weighting throughout the grid surrounding an observation. Consequently the introduction of any one observation yields equivalent corrections at equal distances from the observation. An elliptic along-the-wind enhancement of the weight function is applied by replacing K in equations (A-3) and (A-4) by

$$K = K(1 + \alpha \cos^2 \phi) \qquad (A\text{-}5)$$

The variation of K is a function of both wind direction and speed. In this equation ϕ is the angle between the wind vector and the position vectors from the observation to the grid points and α is defined as the ratio between the wind speed and some characteristic value of the wind speed. As Barnes (1973) points out, the characteristic wind speed should be large enough to modify the radius of zero corrections by a factor ranging from one to about three.

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